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# Multi-Use Rate Disturbance Observer Controller (Project Have MURDOC)

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**FINAL TECHNICAL INFORMATION MEMORANDUM**




**AIR FORCE FLIGHT TEST CENTER**
**EDWARDS AIR FORCE BASE, CALIFORNIA**
**AIR FORCE MATERIEL COMMAND**
**UNITED STATES AIR FORCE**

This Technical Information Memorandum, Have MURDOC: Multi Use Rate Disturbance Observer Controller was prepared and submitted under job order number MT09A500 by the Have MURDOC test team, USAF Test Pilot School, Edwards AFB, California 93524-6485.

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This report presents the results of the Have MURDOC test management project. Have MURDOC demonstrated the use of a simple feedback flight control law that was designed to control flight and generate desired handling qualities throughout the design flight envelope. This was done by applying a pitch-rate feedback flight control law to the Variable In-flight Simulator and Test Aircraft (VISTA) and conducting 12 test flights with the controller, also known as a disturbance observer (DO), providing the input signal to the horizontal tail surfaces. The primary objective was to demonstrate longitudinal flight control using the DO. Programmable test input steps and doublets were used to measure the short period response of the VISTA at various altitudes and airspeeds and compare it to predictions based on simulation. Handling qualities were evaluated in the approach configuration as a buildup to demonstrating a low approach and runway touchdown.

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# EXECUTIVE SUMMARY

This test report presents the results for the Have MURDOC Test Management Project (TMP). The Have MURDOC test team from the USAF Test Pilot School (TPS) at Edwards AFB, CA performed a flight test to demonstrate the use of a simple feedback flight control method that shapes the control surface input to generate a desired aircraft response.

The Have MURDOC TMP was conducted at the request of the Air Force Institute of Technology (AFIT) in collaboration with the U.S. Air Force Test Pilot School (TPS). The Commandant of USAF TPS directed the program. All testing was accomplished under TPS Job Order Number MT09A500. Twelve test sorties were flown on the Variable stability In-flight Simulator and Test Aircraft (VISTA) between September 10, 2009 and September 23, 2009 totaling 16.4 flight hours. Additionally, three T-38A target sorties were flown totaling three flight hours. All sorties were flown in R-2508 complex.

The primary test objective was to demonstrate longitudinal flight control using a pitch rate feedback flight controller. The controller known as a disturbance observer (DO) was designed to force the short period dynamic mode to follow specifications chosen by the user. A variety of flight maneuvers including aerobatics, programmable test input (PTI) steps, and doublets were flown within the flight envelope from 10,000 to 20,000 feet Pressure Altitude (PA) and between 0.4 and 0.8 Mach. Ground simulation using the DO to control a model of the VISTA produced aircraft instabilities. A gain was applied to the elevator command signal that stabilized the aircraft while maintaining acceptable performance. The „command gain" was scheduled based on aircraft dynamic pressure. Controller performance was consistently less damped than desired and sensor noise was not attenuated as predicted, however, neither issue was objectionable and data collection was not affected.

The secondary objective was to demonstrate a 50 feet low approach and was used as a buildup to completing the final objective to demonstrate a touchdown. Handling qualities tracking tasks resulted in Cooper-Harper (CH) ratings ranging from 3 to 4 and pilot-in-the-loop oscillations (PIO) ratings from 1 to 4. Ratings were consistent with what was expected from the results found during the pursuit of objective 1. Handling was acceptable for powered approach.

The final objective was to demonstrate a touchdown. Multiple touch-and-go landings were conducted and handling was consistent with objective 1 and 2 results. The DO exhibited lower pitch damping than desired yet was not objectionable for landing.

All objectives were met.

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# INTRODUCTION

## General

This Test Management Project (TMP) demonstrated the use of a feedback flight control method that was designed to control flight and generate desired handling qualities. This was done by applying a pitch-rate (q) feedback flight control law to the Variable In-flight Simulator and Test Aircraft (VISTA) and conducting 12 test flights with the controller, or disturbance observer (DO), providing the input signal to the elevator. The primary objective of the Have MURDOC TMP was to demonstrate longitudinal flight control. The secondary objective was to demonstrate an approach to 50 feet low approach. The final objective was to demonstrate a touchdown.

The Have MURDOC TMP was conducted at the request of the Air Force Institute of Technology (AFIT) in collaboration with the U.S. Air Force Test Pilot School (TPS). The Commandant of USAF TPS directed this program. All testing was accomplished under TPS Job Order Number MT09A500. Twelve data sorties were flown on the NF-16 Variable stability In-flight Simulator Test Aircraft (VISTA) between 10 September, 2009 and 23 September, 2009 totaling 16.4 flight hours. Additionally, three T-38 target sorties were flown totaling 3 flight hours. The sorties were flown in the R-2508 complex.

## Background

Traditional flight control systems used on advanced aircraft such as the F-16 Fighting Falcon use a complex feedback architecture that is highly dependent on gain scheduling. Fine tuning of the control system is time consuming and difficult to produce MIL-STD-1797B (reference 1) defined Level 1 handling qualities throughout the flight envelope. Further, loss of sensed air data leads to diminished capabilities due to the inability to gain schedule following such a failure. The DO uses a feedback architecture (figure 1) that produces closed-loop dynamics that followed desired flying qualities specifications chosen by the user.

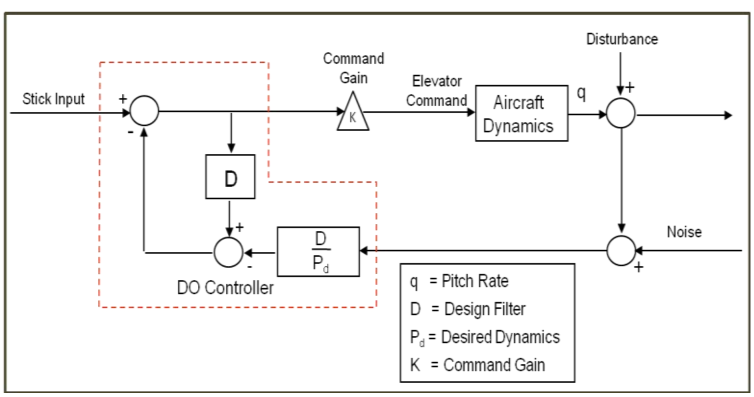


**Figure 1: Disturbance Observer Architecture**

The theory and design of the DO in figure 1 is discussed in reference 2. The VISTA model was used to design the pitch rate feedback controller that is theoretically not dependant on air data or gain scheduling to generate predicted handling qualities. As a consequence, the DO could therefore be used as a „get-home" flight control mode in the case of air data loss as well as a primary flight control system for designers of stealth aircraft that would like to avoid using pitot probes and static ports to aid flight control. The DO controller had never been used on an aircraft prior to the Have MURDOC TMP.

## Program Chronology

A joint Technical Review Board (TRB) and Safety Review Board (SRB) were conducted on August 10, 2009. The TRB was chaired by Ms. Mary McNeely, USAF TPS/ED. The SRB was chaired by Mr. Rob Warner of AFFTC/SET.

The test project consisted of controller model integration by Calspan Corporation, Buffalo, NY, one day of VISTA integration and checkout, 12 test sorties (16.4 hrs), and three T-38A target sorties (3 hrs). All sorties were flown within the R-2508 complex at Edwards air Force Base, California. Controller integration occurred during August 2009, VISTA integration occurred on September 8, 2009 and flight testing occurred from 10 to 23 September, 2009.

## Test Item Description

### Disturbance Observer

The DO used for this project was a feedback flight control method consisting of a second order transfer function defining the desired dynamics, $P_d$, and a second order „design filter" (D) (see figure 1). When implemented on the pitch-rate feedback loop, an elevator control surface command signal was generated that acts to produce the desired pitch rate response. Since pitch-rate was the only feedback signal, the controller was theoretically not dependant on air data in determining the correct control surface input as it was in gain scheduled systems. Desired dynamics are chosen using the short period approximation of the pitch rate response to an input. Based on specifications listed in MIL-STD-1797B for pitch rate flying qualities shown in table 1 and figure 2, a second order transfer function was chosen to represent the „desired dynamics" of the system. The values chosen in reference 2 and used in this project are shown in the following transfer function:

$$P_d = \frac{4^2}{s^2 + 2 \cdot 0.5 \cdot 4 \cdot s + 4^2}$$

where $P_d$ is referred to as the “desired dynamics.”

**Table 1: Pitch Rate Flying Qualities Specifications**

| Level | Effective Time Delay | Transient Peak Ratio | Effective Rise Time* | |
|---|---|---|---|---|
| | | | Flight Phase Categories A and B | Flight Phase Category C |
| 1 | $t_1 \le .12$ sec | TPR $\le .3$ | $9/V_T \le \Delta t \le 500/V_T$ | $9/V_T \le \Delta t \le 200/V_T$ |
| 2 | $t_1 \le .17$ sec | TPR $\le .6$ | $3.2/V_T \le \Delta t \le 1600/V_T$ | $3.2/V_T \le \Delta t \le 645/V_T$ |
| 3 | $t_1 \le .21$ sec | TPR $\le .85$ | | |

*$V_T$ is true airspeed in ft/sec

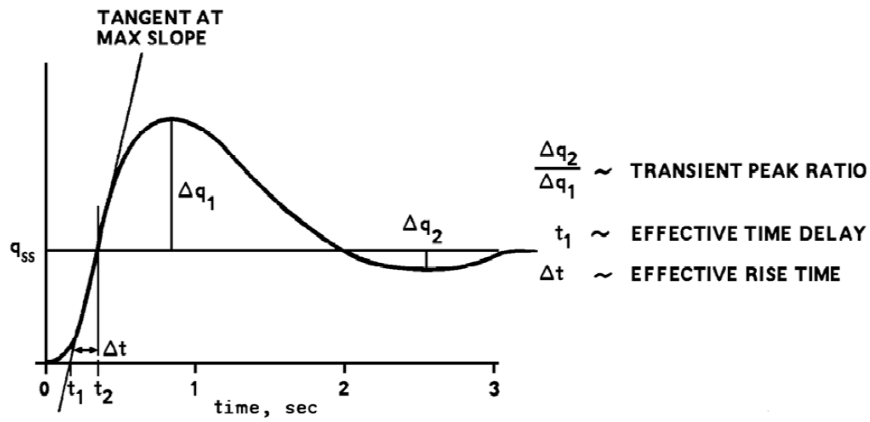


**Figure 2: Pitch Rate Flying Qualities Specification**

After establishing the desired dynamics, the design filter is determined using design methods discussed in reference 2. The design filter below was chosen by the authors of reference 2 and was used for this project:

$$D = \frac{26.5^2}{s^2 + 2 \cdot 0.5 \cdot 26.5 \cdot s + 26.5^2}$$

The „command gain," K, was used to change the sign of the signal going to the control surface actuator. Previous research conducted at the Air Force Institute of Technology (AFIT) produced simulation results using the above reference 2 values for $P_d$ and D and a command signal gain of K = -1. The model used for simulation was an F-16 generated from data presented in reference 3 and was considered to have lower fidelity than the VISTA model used in reference 2. The controller theory, however accounted for model uncertainty, therefore the „AFIT F-16 model" was considered adequate for continued research using the filters developed in reference 2. Figures 3 and 4 show the results of a non-linear simulation with the aircraft center of gravity (CG) set to 30% mean aerodynamic chord (MAC). Figure 3 is the AFIT F-16 model open-loop response to a „singlet" at four corners of the flight envelope (0.4 - 0.8Mach and 5,000-25,000ft). A singlet is half of a doublet as defined in MIL-STD-1797B. Figure 4 shows the AFIT F-16 model response to the same singlet with the DO in the feedback loop. The shape of the closed-loop response demonstrates the DO‟s ability to track desired dynamics.

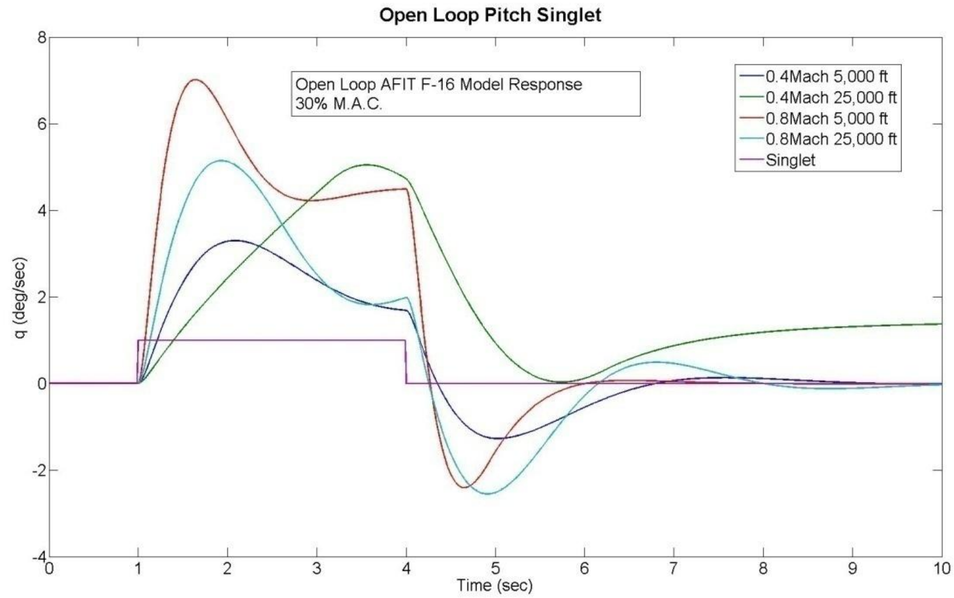


**Figure 3: AFIT F-16 Model Open Loop Response**

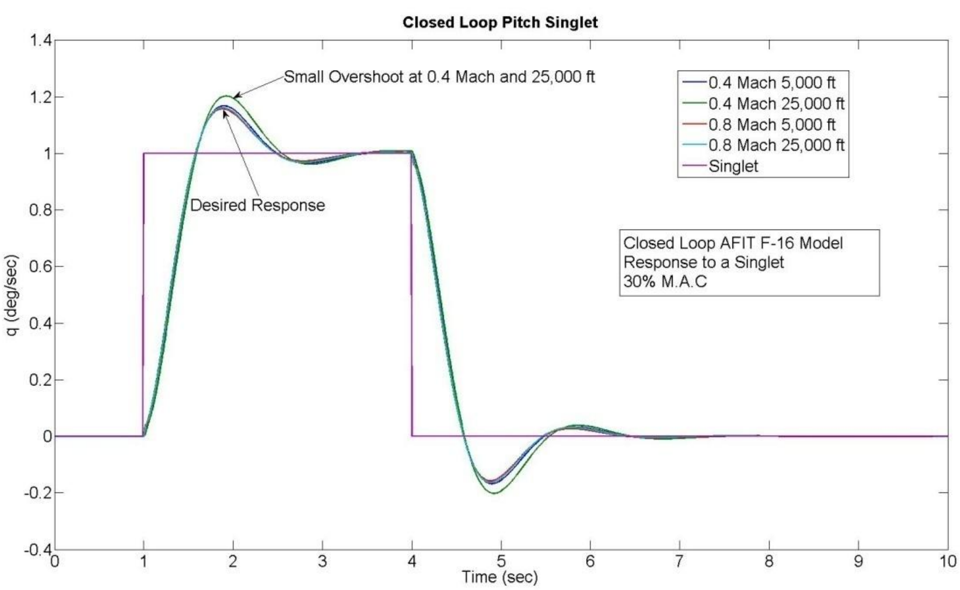


**Figure 4: AFIT F-16 Model Closed Loop Response**

### Research Vehicle

The VISTA (figure 5) was a highly modified Peace Marble II Block 30 F-16D with Block 40 avionics. It was capable of high fidelity simulation of "model" aircraft characteristics in the real flight environment. Airframe modifications included a large dorsal, heavy duty landing gear, programmable heads-up-display (HUD), variable feel system for center stick, and high performance control surface actuators. The VISTA Simulation System (VSS) used five control surfaces and the engine to mimic the feel and response of the simulated aircraft. The VSS could be modified with different control architectures for the purpose of evaluating new control systems such as the DO. The VSS also contained a complete aircraft model that enabled the aircraft to be „flown‟ on the ground. The system Evaluation Pilot (EP) occupied the front cockpit and the Safety Pilot (SP) occupied the rear cockpit. In the VSS mode, Programmable Test Inputs (PTI) could be initiated by either cockpit to evaluate the dynamic response of the aircraft and/or controller performance.


**Figure 5: VISTA**

The Digital Flight Control Computer (DFLCC) continually monitored pilot inputs for safety. If the VSS commands to the control surface actuators approached basic aircraft limits, the DFLCC would disengage the VSS and revert to the basic F-16 control mode. The VSS also included dual sensors for all required signals and sensor failure would cause an automatic safety trip. Either pilot could initiate a manual safety trip as well. Following a safety trip, aircraft control instantly returned to the Safety Pilot occupying the rear cockpit.

## Test Objectives

The Have MURDOC TMP focused on three objectives with the first being the primary objective. Subsequent objectives were only met upon successful completion of the previous objective.

Primary Objective: Demonstrate longitudinal flight control with the disturbance observer providing the horizontal control surface commands to the VISTA.

Secondary Objective: Demonstrate an approach to 50 feet low approach with the disturbance observer providing the horizontal control surface commands.

Tertiary Objective: Demonstrate a touchdown with the disturbance observer providing the horizontal control surface commands.

All objectives were met.

# TEST AND EVALUATION

The pitch axis disturbance observer (DO) was implemented on the USAF Test Pilot School (TPS) „handling qualities simulator" which offered a high fidelity model of the Variable stability In-flight Simulator and Test Aircraft (VISTA). The simulator was used to verify DO and VISTA integration and helped the team troubleshoot potential issues prior to controller integration on the VISTA. In addition, programmable test inputs (PTIs) were conducted to determine appropriate input amplitude and duration for use in flight test. The VISTA center stick was chosen to be the primary controller for the flight test. In addition, a nominal lateral-directional flight control law used by Calspan for basic VISTA simulation system (VSS) modes was selected for control in the lateral-directional axes.

The flying portion of this test project consisted of 12 VISTA test sorties (16.4 hrs), and 3 T-38 target sorties (3 hrs). All sorties were flown within R-2508 complex at Edwards Air Force Base, California. Flight testing occurred from 10 to 23 September 2009. The first two test sorties flown on 10 September 2009 were used to validate proper DO integration with the VISTA. In addition, the PTIs that were planned for data acquisition were sampled at several flight test conditions to verify appropriate magnitude and input duration. The VISTA allowed the test team the ability to change PTI variables in-flight. Upon completion of the second test sortie, a set of PTI variables was determined and used for the duration of flight testing. Data were collected during each of the 12 test sorties. Two pilot members of the test team flew four sorties each and the third pilot member flew three sorties. The ninth test sortie was flown by two Calspan instructor pilots in support of the third test objective.

## Ground Simulation

The DO was integrated into the TPS handling qualities simulator early in the test planning to aid in development of PTIs used during flight test. The handling qualities simulator also offered a higher fidelity model of the VISTA than was available during prior research. The VISTA model accounted for leading edge flap schedule and had the ability to select different aircraft configurations and fuel loads. Initial integration of the DO led to surface commands that caused the VISTA simulation to become unstable. It was determined that a time delay of approximately 15 milliseconds was present in the high-fidelity model that was not present in the model previously used during research at the Air Force Institute of Technology (AFIT). Figure 6 shows the time delay present in the high fidelity VISTA model compared to the low fidelity AFIT F-16 model.

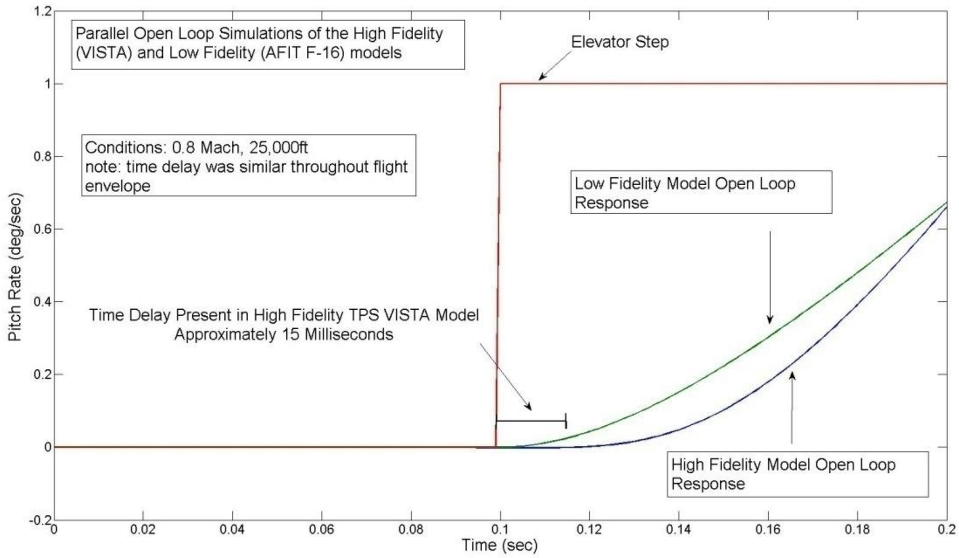


**Figure 6: High Fidelity VISTA Model Time Delay**

The time delay caused the DO to generate control signals that were too large and led to unstable responses from the simulated VISTA. It was determined that a reduction in command gain (K) was required to stabilize the DO controlled VISTA and maintain desired performance (ie. follow the desired dynamics specified in the controller). In addition, the gain required to stabilize the model and maintain performance was different at different dynamic pressures. Therefore, a simple gain schedule (figure 7) was created using a MATLAB® minimization function (see appendix A) that found the optimum K for a given dynamic pressure.

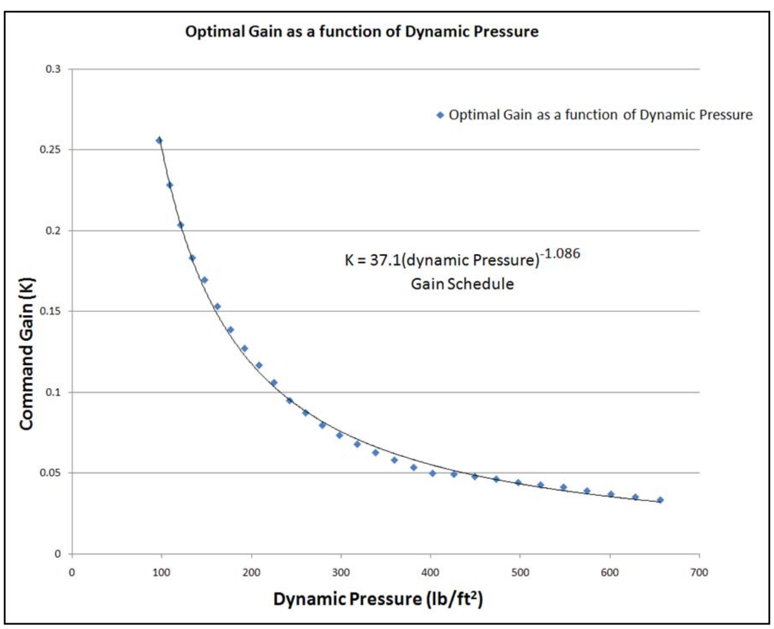


**Figure 7: Command Gain (K) Schedule**

Scheduling the command gain was a departure from the DO controller theory of reference 2 and work that had been done at AFIT using the AFIT F-16 model. The change, however, was necessary to continue with the scheduled flight test. Simulation results with the gain schedule produced the results seen in figure 8 below.

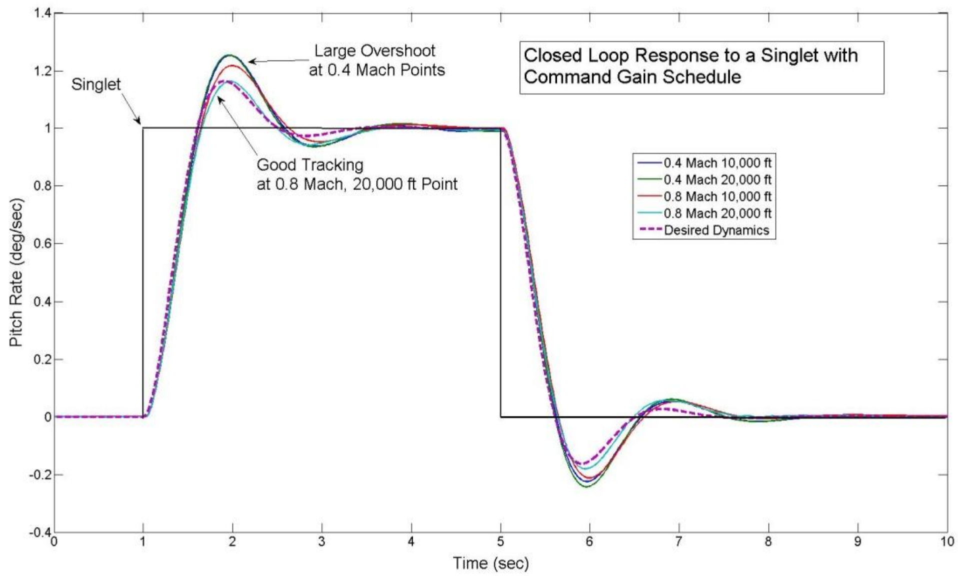


**Figure 8: VISTA Model Singlet Response with Gain Schedule**

Controller performance did not track the desired response as well as with the AFIT F-16 model, however, the TPS VISTA model provided the highest fidelity results and was closer to what was expected during flight test. Simulation results with the gain schedule predicted lower damping ratios (ζ) throughout most of the planned test envelope. The test envelope for objective one was 0.4 to 0.8 Mach and 10,000 to 20,000 feet pressure altitude (PA). In addition, objectives two and three called for operations at approach speeds from 10,000 feet PA down to field elevation. The simulator was used to verify that the VISTA would operate in the landing configuration at speeds equating to 13 degrees angle-of-attack (AOA). Figure 9 shows the results of a simulation conducted with the landing gear down, 2500 pounds of fuel, 10,000 feet PA and 170 knots calibrated airspeed (KCAS) using the gain scheduled controller.

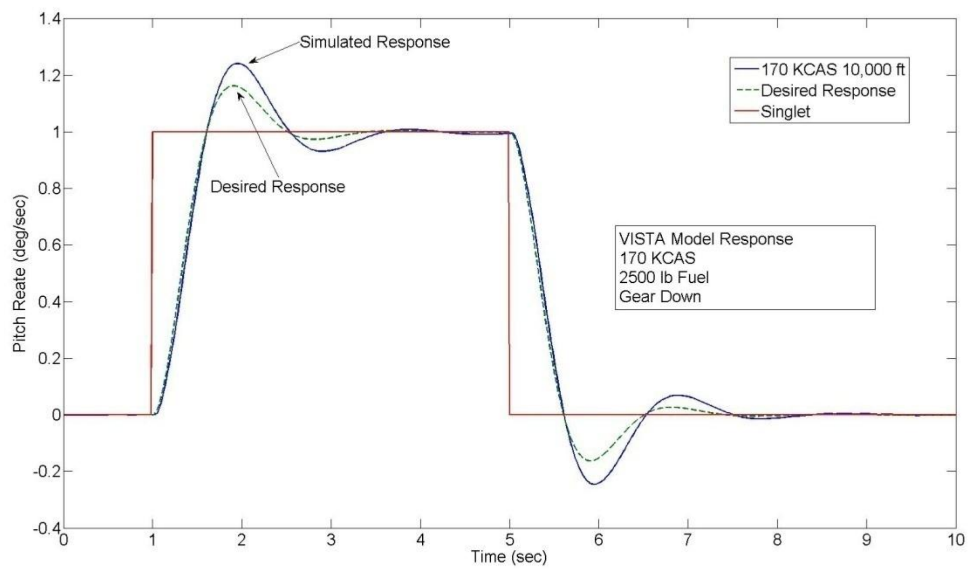


**Figure 9: Closed Loop Approach Configuration Singlet**

Again, the performance was less damped than desired, however, considered to be acceptable for flight.

The ground simulation phase of the test plan concluded with the first departure from DO theory. One of the claims of the theory was that desired performance could be achieved throughout the flight envelope with pitch rate as the only control variable. It was determined, however, that a command gain schedule was required to maintain aircraft stability. Though not ideal, the project continued as the controller could still demonstrate the ability to control longitudinal flight and produce a consistent short period throughout the flight envelope.

## Longitudinal Flight Control

The primary objective of the Have MURDOC test management project (TMP) was to demonstrate longitudinal flight control with the DO providing the control input signal to the elevator. The DO was integrated into the VISTA Simulation System (VSS) by Calspan Corporation. With the VSS engaged, the DO provided the signal to the horizontal tail surfaces on the VISTA. The primary objective was evaluated by activating the VSS at different points in the flight envelope and conducting a series of PTIs and free-flight maneuvers. In addition, simulated turbulence was activated at several flight conditions to observe the DO response to turbulence. Table 2 lists the PTIs, maneuvers flown, and conditions at which they were flown. All test points were flown at each airspeed and altitude combination listed in table 2.

**Table 2: Longitudinal Flight Control Test Points**

| Conditions* | | Programmable Test Inputs | Maneuvers* |
|---|---|---|---|
| Speed (Mach) | Altitudes (ft) | | |
| 0.4 | 10,000 | Step | Loop |
| 0.6 | 15,000 | Doublet | Sliceback |
| 0.8 | 20,000 | Simulated Turbulence | Slow-Down Turn |

* All PTIs were flown at each altitude and speed combination. Maneuvers were flown within the previously cleared flight envelope.

*Open Loop Stability*

The DO controlled VSS was engaged to determine basic aircraft stability. With the VISTA trimmed for wings level, 1g flight, the VSS was engaged at each of the flight conditions listed in table 2. The evaluation pilot provided no input to the control stick and data were collected for a minimum of 10 seconds. Atmospheric turbulence was minimal during the completion of open loop stability test points. With the VSS engaged, the horizontal tail surfaces tended to „buzz‟ (oscillate) at a high frequency. The horizontal tail buzz was determined to be due to high frequency sensor noise that was amplified rather than attenuated by the DO. Figure 10 shows the horizontal tail command signal before and after VSS engagement.

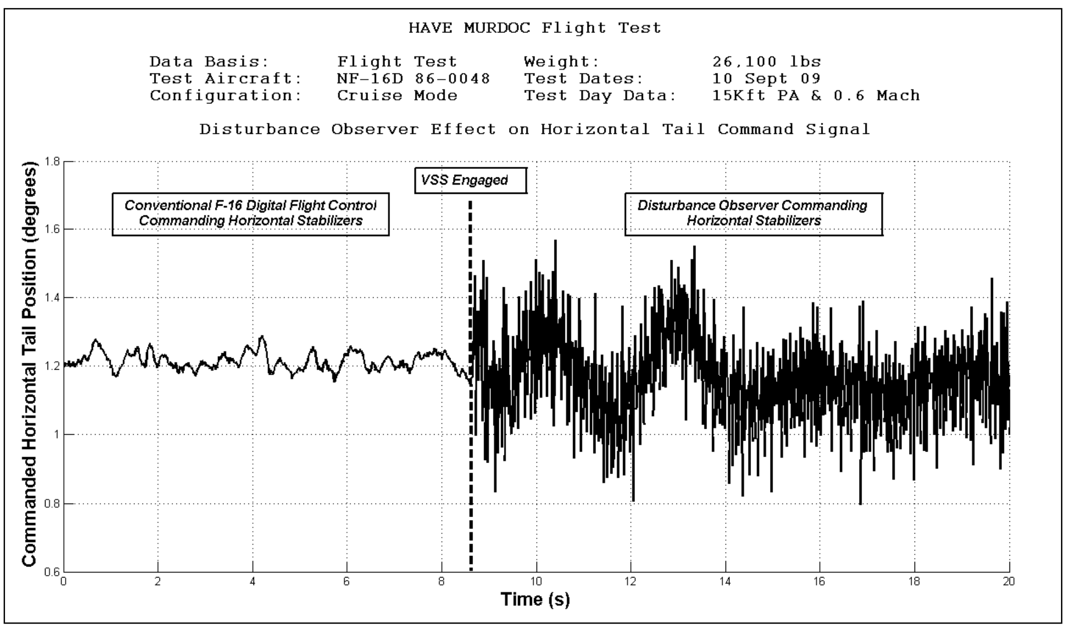


**Figure 10: Horizontal Tail Command Signal**

It was clear that the DO was acting to amplify pitch rate sensor noise, a result that was counter to the design. The controller was theorized to act as a low pass filter, attenuating signals with frequencies higher than the design filter frequency of $\omega_d$ = 26.5 rad/sec. However, the noisy feedback signal was amplified by an amount proportional to the ratio:

$$\frac{(Design\ filter\ frequency)^2}{(Desired\ dynamics\ frequency)^2} = \frac{(26.5)^2}{(4)^2}$$

Figure 11 shows a representative flight test result of the pitch rate signal noise amplification after passing through the DO filter, D/$P_d$.

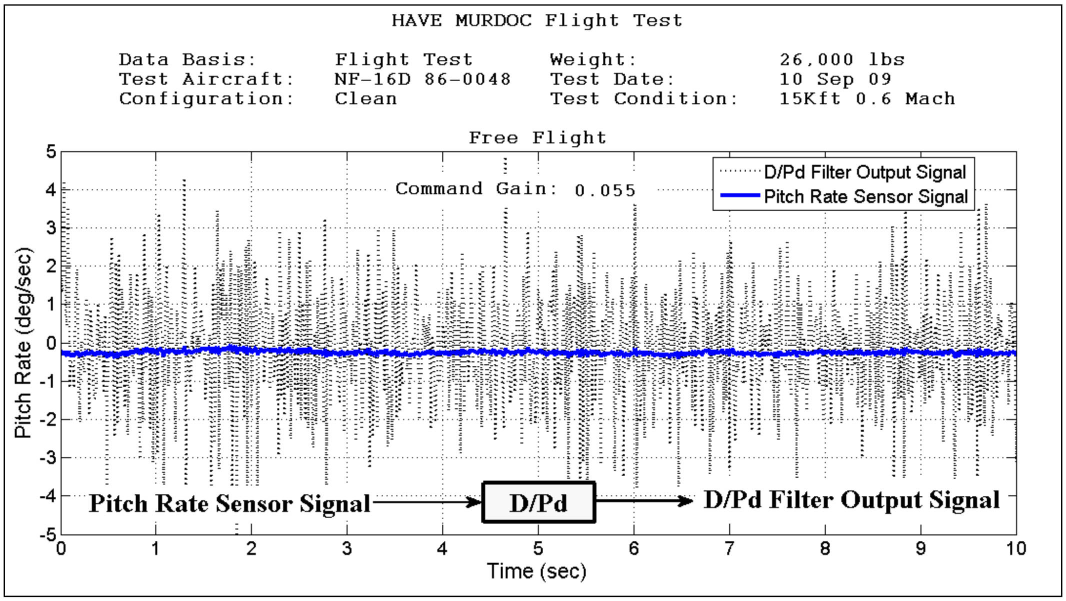


**Figure 11: DO Pitch Rate Sensor Noise Amplification**

The filter output signal contained noise that was roughly twenty times the magnitude of the pitch rate sensor noise. The large amplitude, high frequency error signal was then passed to the horizontal tail actuator and created the buzz witnessed by the evaluation pilot. The horizontal tail buzzing was not detrimental to the collection of data and testing continued. The signal noise amplification was not desired, however, and future DO research should include determining ways to attenuate signal noise while maintaining controller performance. The VISTA simulator had the capability of adding sensor noise to the feedback signal. This capability was implemented and the flight test „noise amplification" results were replicated in the simulator. A preliminary look into reducing elevator command signal noise resulted in a reduction of the design filter frequency to a value closer to the desired dynamics frequency. This reduced the signal noise, however, the DO performance had changed.

*Response to Programmable Test Inputs*

The DO performance was evaluated by conducting PTI steps and doublets at each point in the flight test envelope. Performance was determined by calculating short period natural frequency ($\omega_n$) and damping ratio ($\zeta$) and comparing them to the desired response values specified in the controller. The „logarithm decrement" method defined by the equation below was used to calculate ζ.

$$\zeta = \frac{1}{\sqrt{1 + \left(\frac{2\pi}{\ln\left(\frac{x_0}{x_1}\right)}\right)^2}}$$

The variables $x_0$ and $x_1$ are the pitch rate values of the first and second overshoot peaks respectively. The short period natural frequency, $\omega_n$, was calculated using:

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}}$$

where $\omega_d$ is the observed „damped natural frequency" determined by applying the equation:

$$\omega_d = \frac{2\pi}{T}$$

The period (T) is determined by measuring the time between two overshoot peaks. Figure 12 shows a representative plot of a short period response to a step input and the values used to calculate $\omega_n$ and ζ . The logarithm decrement method for calculating ζ and $\omega_n$ is only useful with systems that have damping ratios of 0.5 or less.

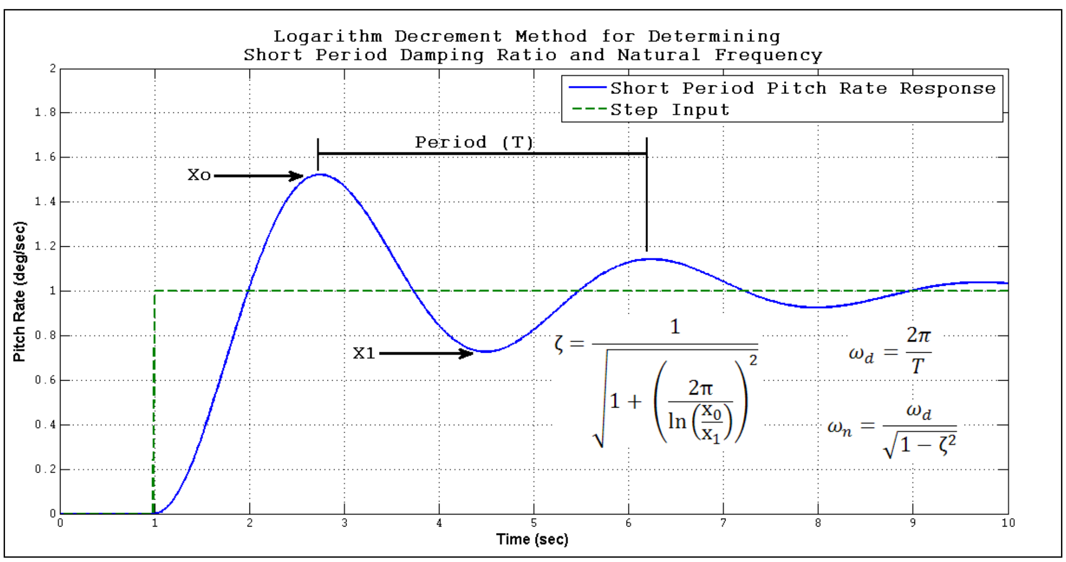


**Figure 12: Logarithm Decrement Method**

At each flight condition listed in table 2, both step and doublet PTIs were engaged from straight and level, 1g flight. The evaluation pilot made no stick input for the four second duration of each PTI step and attempted to allow the aircraft response to completely damp out prior to recovering from a PTI doublet. Figure 13 presents the flight test results of a PTI step response at 20,000 feet pressure altitude (PA) and 0.6 Mach.

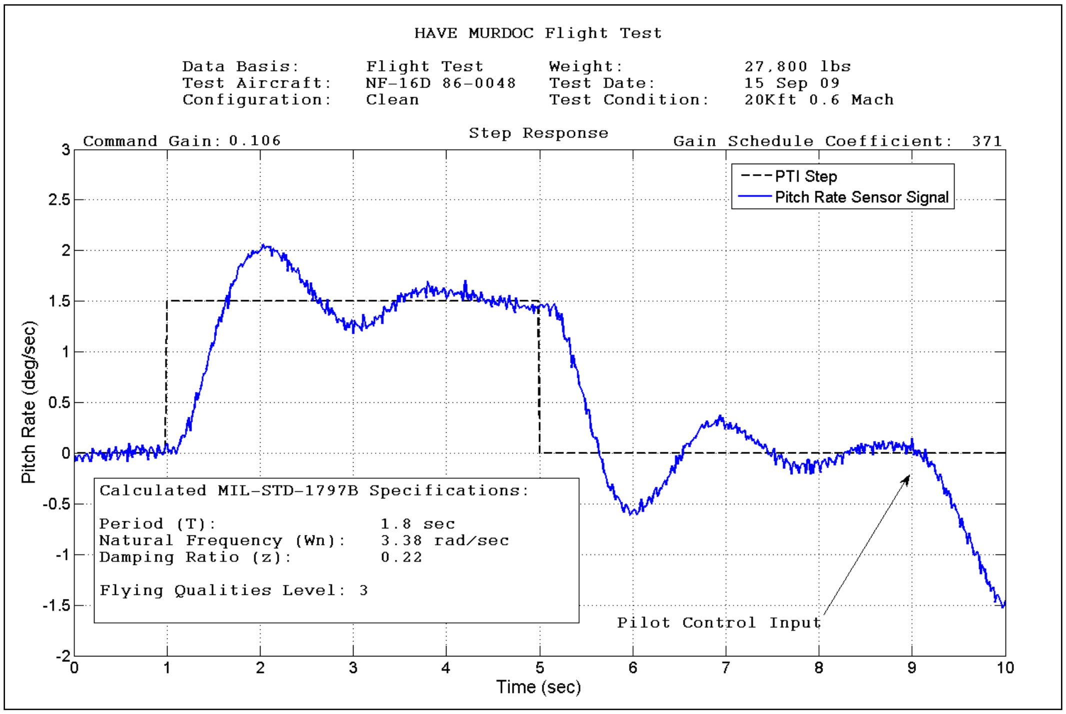


**Figure 13: Short Period Response to a PTI Step (20K, 0.6 Mach)**

Natural frequency and damping ratio were calculated to be 3.38 rad/sec and 0.22 respectively for the initial step. The values meet the MIL-STD-1797B specifications for predicted level 3 flying qualities. In general, for each PTI, the calculated $\omega_n$ and $\zeta$ were slightly slower and significantly less damped than the „desired" values of $\omega_n$ = 4rad/sec and $\zeta$ = 0.5. This result was consistent with results found during simulation (see figure 8). In no case was the natural frequency or damping ratio during flight test faster or more damped than the controller specified values.

A PTI doublet at 20,000 feet PA and 0.6 Mach produced similar results as the step at the same condition (figure 13). The natural frequency and damping ratios were calculated to be 3.42 rad/sec and 0.25 respectfully. Again, the calculated values predict MIL-STD-1797B level 3 flying qualities due to the low damping ratio.

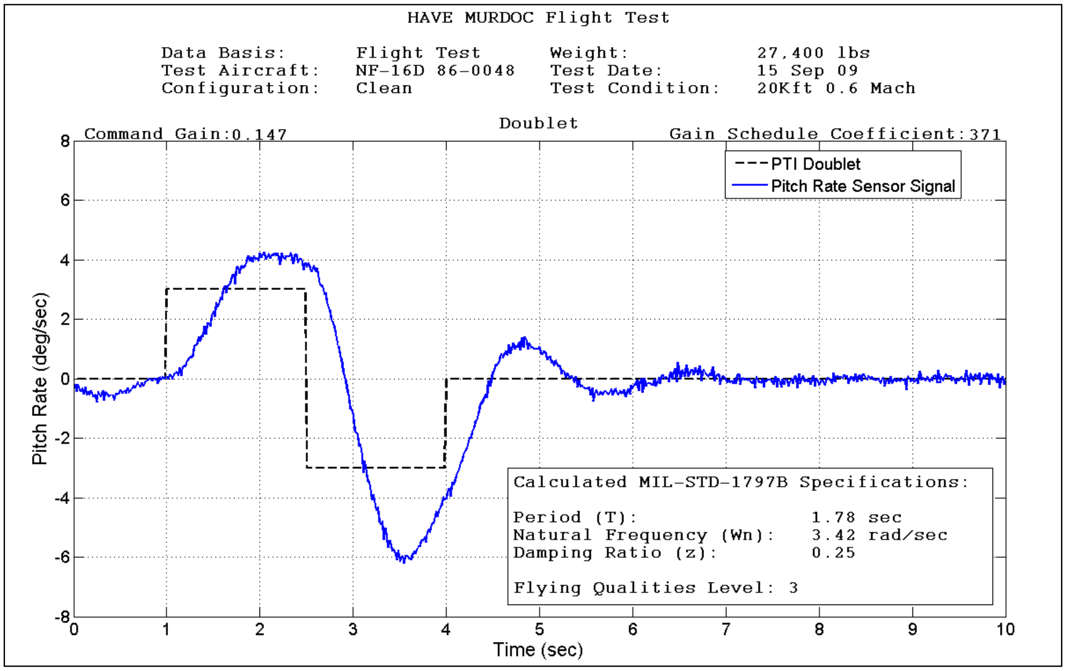


**Figure 14: Short Period Response to a PTI Doublet (20K, 0.6 Mach)**

One of the concepts of the DO controller theory was that the short period response to a given input would be similar regardless of flight condition. Figure 15 displays the VISTA response to identical PTIs initiated at three different flight conditions.

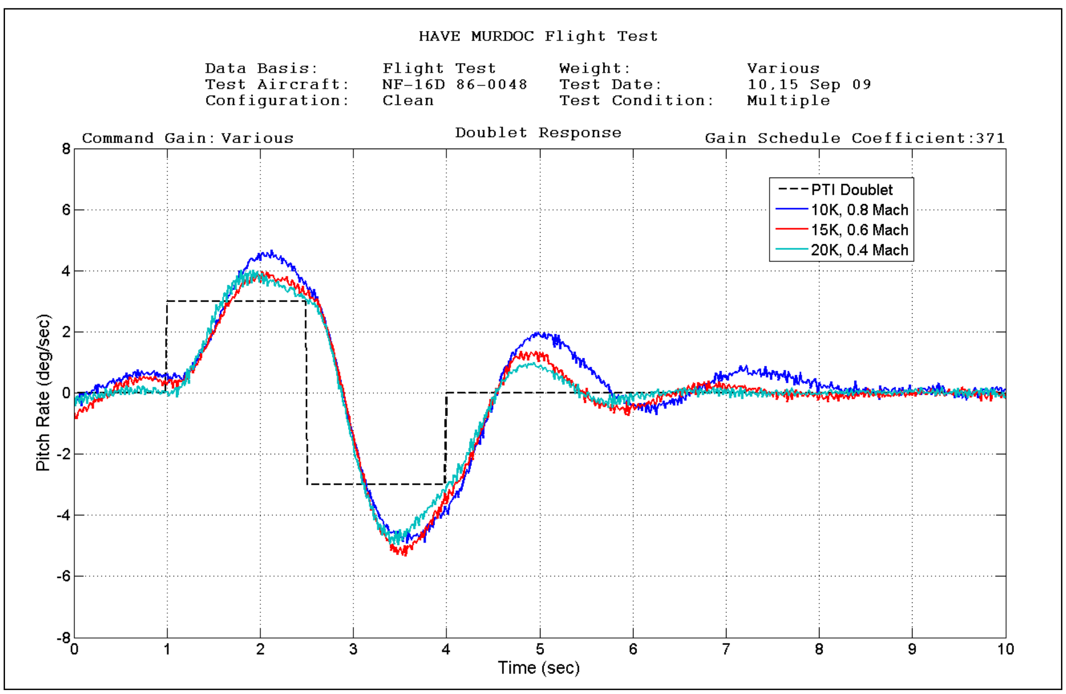


**Figure 15: Doublet comparison at Three Different Flight Conditions**

Though not identical, the responses were similar and demonstrated the DOs ability to shape the horizontal tail surface command appropriately despite large differences in dynamic pressure. Again, this result was similar to ground simulation results with the gain schedule applied to the command gain (see figure 8). Of note, however, is that the high dynamic pressure point (10K, 0.8 Mach) produced a large overshoot during flight test when simulation predicted that the low dynamic pressure point (20K, 0.4 Mach) would generate the largest overshoot.

*Maneuvering Flight*

Standard F-16 aerobatic maneuvers were flown to qualitatively assess the handling qualities[1] during maneuvering flight with widely varying dynamic pressures. Loops, slicebacks[2], and slow down turns were flown within the previously cleared flight envelope of altitudes, airspeeds, and angles of attack (AOA) to assess the longitudinal control characteristics of the DO as airspeed, load factor, and AOA were varied. The loop was entered at military power with a 4 g pull at 430 KCAS. The pitch control was modulated to maintain 200 KCAS at the top of the loop with a maximum AOA of 13 degrees. The loop was completed with a 4 g pull to capture 400 KCAS. The sliceback was completed at 400 KCAS, military power and 120 degrees of bank. Load factor was varied to maintain 400 KCAS through the maneuver. The slow down turns were flown at 350 KCAS and 400 KCAS. The turns were executed with idle power and a 5 g level turn until 200 KCAS was reached. Throughout the tested envelope, the DO qualitatively performed predictably and satisfactorily for longitudinal control during maneuvering flight. This result was consistent with what was expected from simulation results with the gain schedule applied.

## Approach to 50 feet Low Approach

The secondary objective of the Have MURDOC TMP was designed to present a build-up to the final project objective of demonstrating a runway touchdown. Other than aerobatics, the objective consisted of the same flight test techniques (FTTs) used during completion of the primary objective and included handling qualities investigations while in the powered approach configuration. In addition, simulated low-approaches were evaluated above 10,000 feet PA prior to conducting the 50 feet AGL low-approach. Three target sorties were flown with a T-38 in support of the secondary objective. The target T-38s were used for the handling qualities evaluations and each of the project pilots flew a test sortie with a target prior to completing a low approach to 50 feet AGL.

---

[1] „Flying qualities" refer to an aircraft"s open loop characteristics (ie. response to PTIs where the pilot is out of the control loop). „Handling qualities" refer to the pilot-in-the-loop characteristics of the aircraft and the primary form of handling qualities data are pilot comments.

[2] Flight maneuver from which the aircraft is rolled to a bank angle greater than 90 degrees then a straight pull is made until the aircraft pitch attitude is level with the horizon and the bank angle is less than 90 degrees. Usually a 180 degree heading change occurs with a complete maneuver.

*Powered Approach Stability*

The DO controlled VISTA was flown in the powered approach configuration (landing gear down) at speeds ranging from 220 KCAS to 11 degrees AOA (approx. 160 KIAS) to demonstrate basic aircraft stability. Similar to the *open loop stability* investigation described above, the VSS was engaged and with no pilot input, data were collected for a minimum of 10 seconds. All powered approach points were collected at 10,000 feet PA. The results in the powered approach configuration were similar to the clean configuration points. The aircraft continued to present the same horizontal tail „buzz" witnessed during all previous test sorties. The magnitude of the horizontal tail deflection buzz was larger than during the cruise configuration points and visible to the pilot. The buzzing was determined to be due to the magnification of pitch rate sensor noise as discussed previously. The larger magnitude of the deflection was due to the larger surface movement required to generate a pitch rate at lower dynamic pressures. The VISTA was stable in the powered approach configuration at approach speeds.

*Response to Programmable Test Inputs*

The DO performance was evaluated in the powered approach configuration by conducting PTI steps and doublets at 220KCAS, 11 deg AOA (typical F-16 approach AOA) and 10,000 feet. Performance was determined by calculating short period natural frequency ($\omega_n$) and damping ratio ($\zeta$) and comparing them to the desired response values specified in the controller. PTIs were executed in a similar manner to those conducted during cruise configured flight. Initial attempts at generating the PTIs resulted in multiple „surface-rate-limit" trips of the VSS. The rate limit trips were caused by the horizontal tail surface command signal exceeding VISTA safety trip limits. Simulation did not predict this result because pitch-rate sensor noise was not simulated prior to flight test. The large control deflections required at low dynamic pressures in conjunction with sensor noise caused the surface command signal to exceed the VSS actuator rate limits. The command signal gain[3] (K) was reduced from 371 to 170 and subsequent PTIs were completed without rate limit trips. Figure 16 shows the effect of reducing the command gain at 10,000 feet PA and 220 KIAS. The aircraft response was much less damped resulting in multiple overshoots.

[3] The actual command gain coefficients were 37.1 and 17.0 per the gain schedule, however, the VISTA interface convention required removing the decimal.

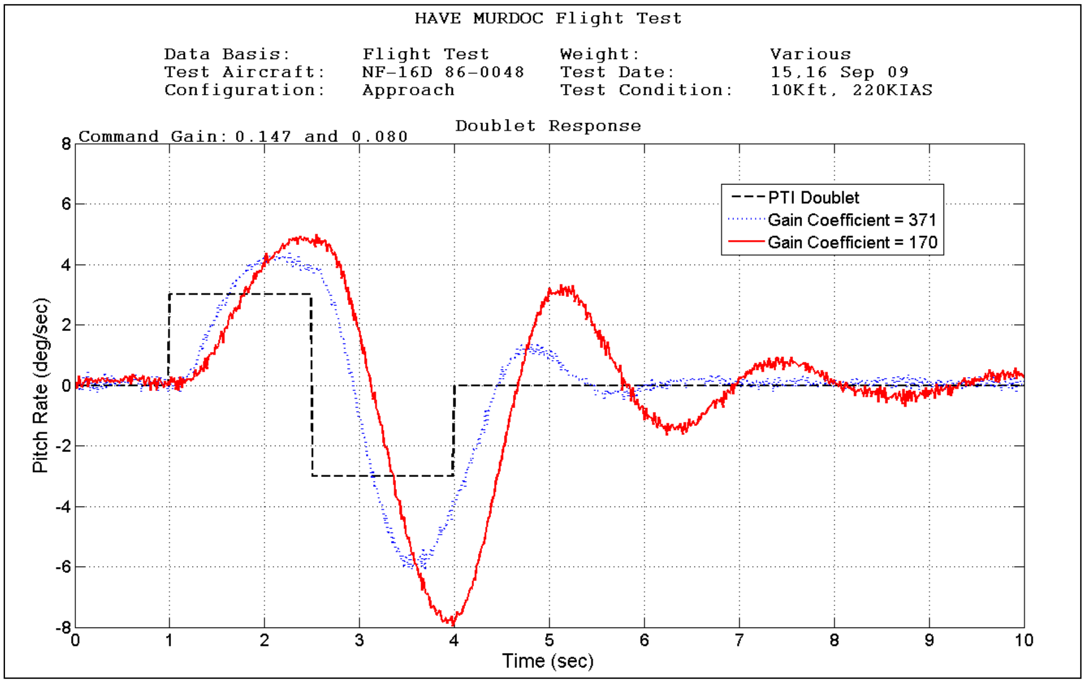


**Figure 16: Command Gain Affect on Doublet Response**

The change in command gain schedule coefficient was necessary, however, to continue with the test plan without risking multiple rate-limit safety trips interrupting data collection during the approach configuration test points. Figure 17 shows the short period response to a doublet with the command gain set to 170.

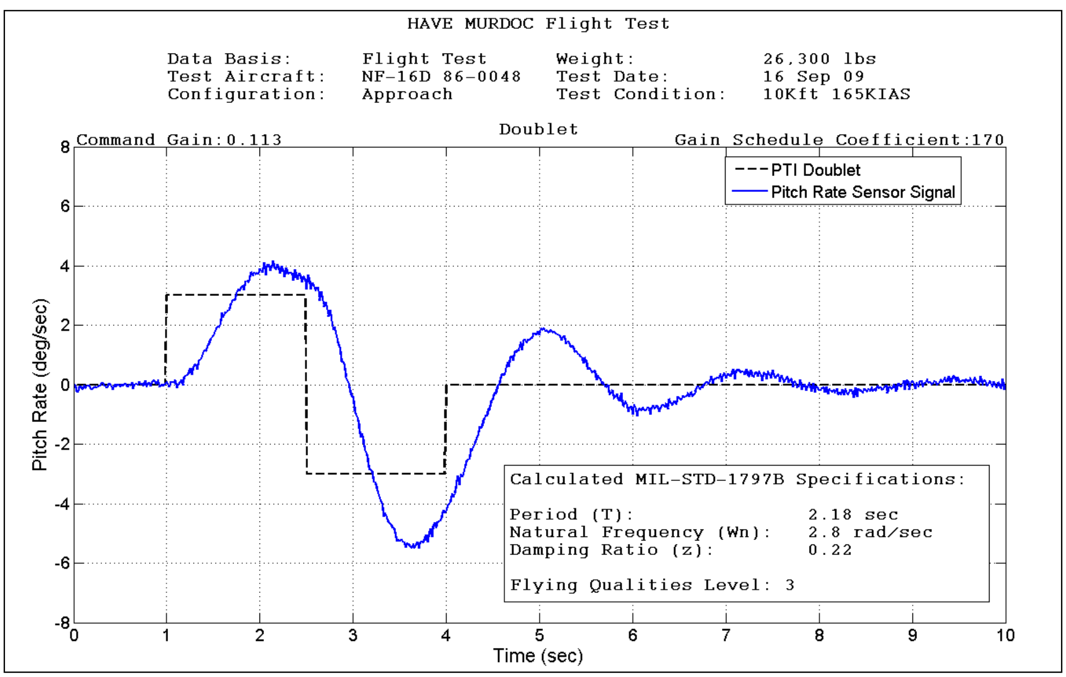


**Figure 17: Powered Approach Doublet Response**

The calculated natural frequency and damping ratio at 10,000 feet PA and 165 KIAS were $\omega_n$ = 2.8 rad/sec and $\zeta$ = 0.22. Again, the short period was characterized by a slower and less damped response. Damping was better at 165 KIAS than 220 KIAS as was evident from the higher magnitude and increased number of overshoots at 220 KIAS (figures 16, 17, and Appendix C). The effect of the slower and less damped response during flight test was evaluated during the handling qualities evaluation FTTs and discussed in the *powered approach handling qualities* paragraph below.

*Response to Simulated Turbulence*

Simulated turbulence was used to qualitatively evaluate the response of the DO to turbulent air as a buildup to the approach and touchdown phases of the test. With the DO engaged, simulated turbulence was activated by the safety pilot and the evaluation pilot maintained pitch and bank within ±5 degrees while assessing ride quality. The simulated turbulence was a feature of the VISTA that fed a horizontal tail command signal directly to the control surface, bypassing the DO control logic. The response of the aircraft was therefore as if it was in actual turbulence. In general, the magnitude of the turbulence model was appropriate and assessed to represent light to moderate turbulence. The pilot commented that the turbulence felt like the lateral component of turbulence was unrealistically large relative to the vertical component. Based on free-flight results, this was assessed to be due to the DOs attempt to generate a zero pitch rate and thus damp out the affect of the vertical component of turbulence. The lateral-directional components of turbulence, however, were not actively damped by the VISTA baseline flight control system. The DO response to turbulence was not objectionable for straight and level flight.

*Powered Approach Response to Turbulence*

Simulated turbulence was used to qualitatively evaluate the DO"s response to turbulent air in the powered approach configuration. With the DO engaged at 10,000 feet and 220 KCAS simulated turbulence was activated by the safety pilot and the evaluation pilot maintained pitch and bank within ± 5 degrees while assessing ride quality. Again, the magnitude of the turbulence model was appropriate and assessed to represent light to moderate turbulence. The pilot commented that the turbulence felt like the vertical component of turbulence was damped relative to the lateral/directional components. As with the clean configuration investigation, this was determined to be due to the DOs attempt to generate a zero pitch rate and thus damp out the affect of the vertical component of turbulence. The DO response to turbulence in the powered approach configuration was not objectionable for straight and level flight at 220 KCAS.

*Powered Approach Handling Qualities*

Handling qualities of the VISTA and DO controller were evaluated through a series of formation tracking tasks. At speeds ranging from 250 KCAS to 11 ± 2 degrees AOA, the evaluation pilot performed tracking tasks and assigned pilot-in-the-loop oscillation (PIO) ratings. A Cooper-Harper (CH) (reference 4) task was performed and a CH rating was recorded along with pilot comments. Tracking tasks included both low gain formation station keeping and high gain tracking. Two techniques were used during the high gain tracking to evaluate whether the aircraft exhibited any instabilities or tendencies to PIO. The „workload buildup‟ technique as discussed in reference 5 involves performing a tracking task while avoiding defined boundaries. Boundaries were treated as critical and every attempt was made to remain within them or the task was terminated. As boundaries were incrementally reduced in size, pilot gains naturally increased and potential handling qualities deficiencies were discovered. The second technique was to accomplish point tracking while attempting to maintain zero error. This technique was used, like the workload buildup technique, to discover potential handling qualities deficiencies as pilot gain increases. To accomplish the tasks, the evaluation pilot flew the VISTA in the route position (10-20 feet wingtip clearance, see figure 18). The pilot started the task with a vertical offset then attempt to capture the projected T-38 wingtip within one of the circles that the star emblem creates on the side of the T-38 as shown in figure 19.

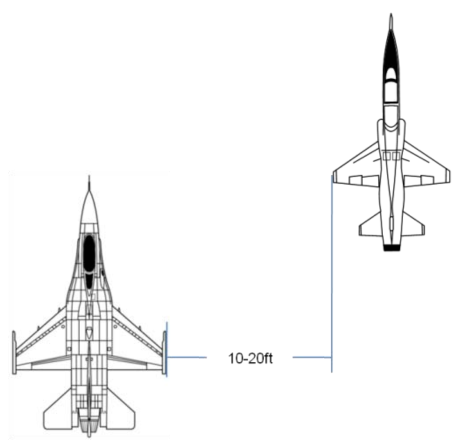


**Figure 18: Tracking Task Wingtip Spacing**

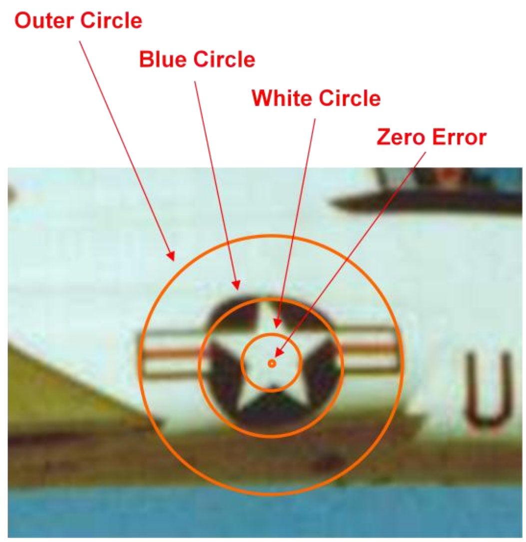


**Figure 19: Tracking Task Visual Reference**

The simulated landing, Cooper-Harper, task was initiated from a stack-high route position (figure 20). The pilot simulated a landing flare by descending to capture the T-38 wingtip projected on the star as in the previous workload buildup task. The CH „desired criteria‟ was to arrest the sink rate within the blue circle (figure 19) with one or less pitch overshoots. „Adequate criteria‟ was attained if the flare was arrested within the outer circle with one or less pitch overshoot.

The second CH task was to fly in the stack-level route formation while the target aircraft performed a series of shallow climbs and descents (±5 degrees pitch attitude). Desired performance was keeping the projected wingtip within the blue circle (figure 19) for 75 percent of a 20 second task. Adequate performance was keeping the wingtip within the outer circle for 75 percent of a 20 second task.

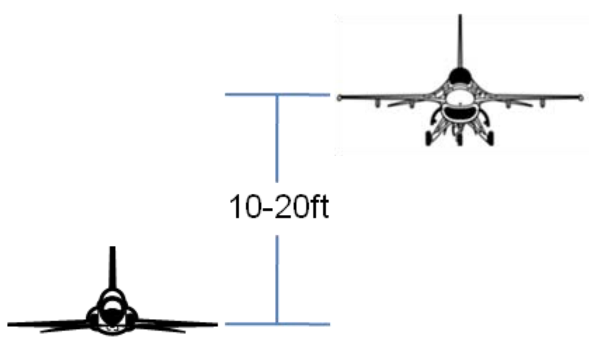


**Figure 20: Cooper-Harper Task Setup**

PIO ratings are tabulated in figure 21 and reflect the ratings associated with the type of task being performed.

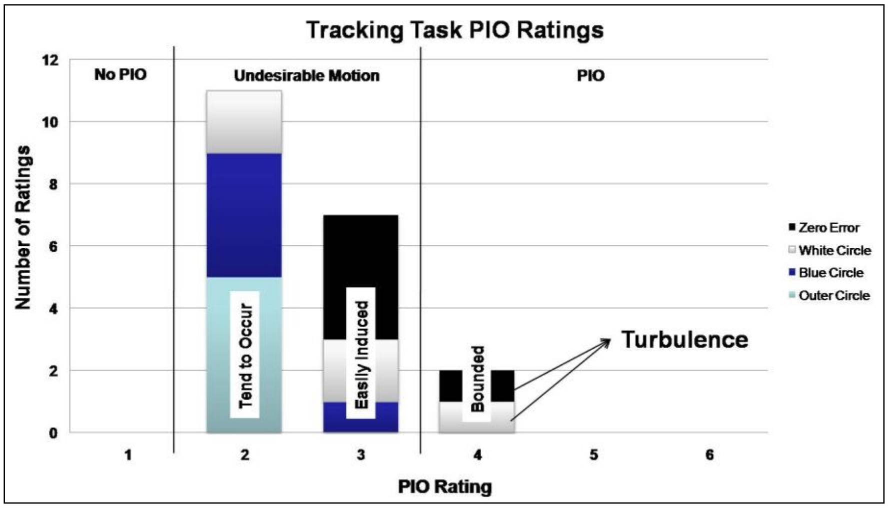


**Figure 21: Tracking Task PIO Ratings**

The pilots noticed a delay between the pitch rate and the change in the flight path during large magnitude inputs. This mismatch made the aircraft response less predictable during tracking tasks. Pilots commented that the nose of the aircraft would move as desired, however the aircraft pivoted about the center of gravity with little change to the flight path. For a series of large inputs, the result was the pilot feeling slightly „out of phase‟ with the aircraft. The PIO ratings of 2 and 3 reflected this characteristic with one pilot noting that his inputs were completely out of phase with the response of the aircraft and assigned a rating of 4. Of note, the tasks that produced the PIO 4 ratings were conducted with light to moderate turbulence and at 220 KIAS where PTIs resulted in the worst short period frequency and damping. The pilot commented that turbulence noticeably effected handling during high gain tracking. Figure 22 shows the PIO ratings assigned during the Cooper-Harper tracking tasks.

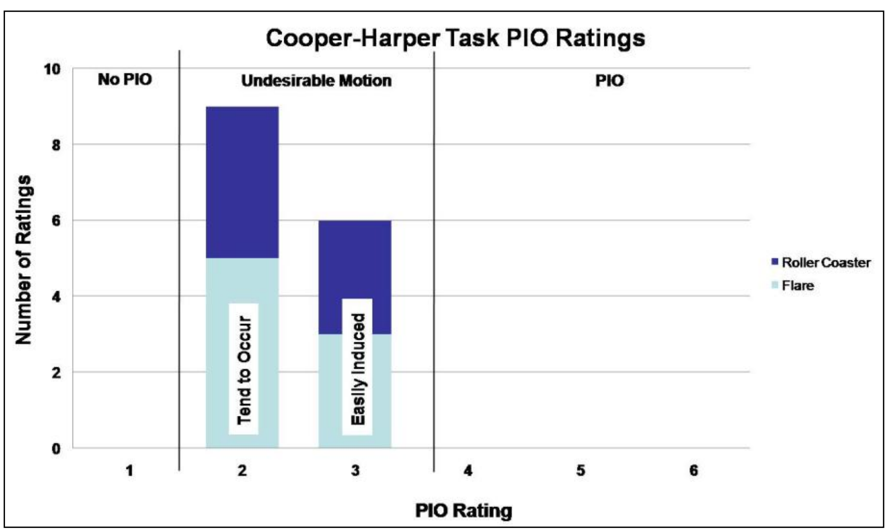


**Figure 22: Cooper-Harper Task PIO Ratings**

The PIO ratings from the CH tasks were similar to the workload buildup task ratings. No PIO occurred and all ratings were either a 2 or 3. The CH ratings for the tasks are presented in figure 23.

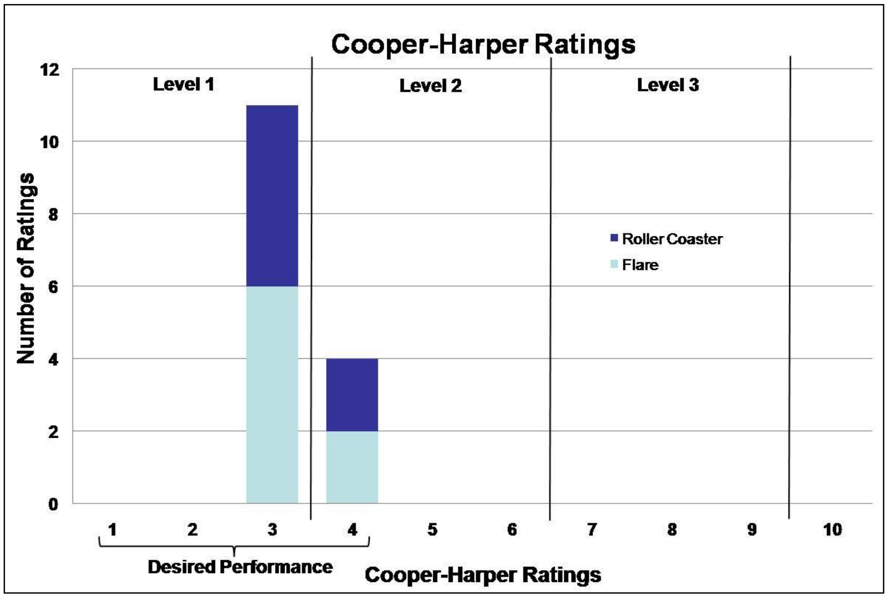


**Figure 23: Cooper-Harper Ratings**

Pilots noted that for slow, small magnitude corrections, the tracking task was tolerable, however larger corrections to formation position revealed the mismatch between the pitch rate and flight path change. The result was often adequate or desired criteria being obtained, but with a high degree of workload and compensation used to maintain the boundaries of the task. Pilots noted that the presence of light turbulence degraded the task performance more than expected. The turbulence reduced the DO bandwidth available to the pilot and during high gain tracking, the performance was reduced. The handling qualities in the powered approach configuration and airspeeds were sufficient for low gain flight and showed a degradation of flight path control for high bandwidth corrections in the pitch axis. The decision to continue to low approach was made based on the tracking task and CH task results. A bounded PIO only occurred during high gain tracking when in turbulent air at 220 KIAS. Therefore, subsequent low approach and touchdown flight was only conducted when there was no turbulence greater than light. In addition, safety procedures were developed from which the pilots assessed their approach parameters at several distances and altitudes during the approach. If the pilot was outside any defined parameters, the approach was terminated and a go-around initiated.

*Low Approach*

Multiple low-approaches were flown by each test team pilot to demonstrate DO control when pilot input gains were increased due to the proximity to the runway. In addition, handling qualities were assessed as a buildup to completing the runway touchdown objective. All approaches were flown with the DO active for the final 4 to 5 miles. Each test team pilot flew their first low approach to a minimum 100 feet AGL go-around and subsequent approaches were flown to 50 feet AGL. Low approach conditions and pilot comments are listed in table 3.

**Table 3: Low Approach Pilot Comments**

| Sortie Number & Date | Pilot Background | Approach Type | Wind Conditions (Runway 22) | Pilot comments |
|---|---|---|---|---|
| 6<br>16 Sep | F-15I<br>F-16I | 100ft | 240/12 | No problems other than trim |
| | | 50ft | 250/15 | Pitch angle capture generates small overshoots. Easily stopped by backing out of control loop. |
| | | 50ft | 240/15 | Smooth |
| 7<br>18 Sep | F-16 | 100ft | 270/8 | Small amplitude pitch oscillations when fine tracking |
| | | 50ft | 260/10 | Smooth deliberate inputs work well. |
| | | 50ft | 260/10 | No issues preventing continue to touchdown |
| 8<br>18 Sep | C-17<br>B-2<br>T-38 | 100ft | 250/12 | Similar to F-16 with slight lag and less damping |
| | | 50ft | 250/10 | Slight pitch bobble during fine tune tracking |
| | | 50ft | 250/10 | Lack of trim requires continuous forward stick compensation (same for all approaches) |

The DO controlled VISTA handling was described as being similar to the F-16 with a less damped response to fine pitch changes. This result was consistent with the handling qualities evaluations previously discussed. None of the approaches flown resulted in objectionable results preventing continued pursuit of the runway touchdown objective.

## Runway Touchdown

The final objective of the Have MURDOC TMP was to demonstrate a touchdown on the runway with the DO controlled VSS engaged. The wind conditions were light and variable during first touchdown sortie and turbulence was negligible. The evaluator pilot that flew the first touchdown sortie made two low-approaches and five runway touchdowns with the VSS engaged.


**Figure 24: First Landing with Disturbance Observer**

The pilot determined the DO controller was not objectionable for approach and touchdown, and the test team continued with the final three sorties. Each project pilot flew one of the final three test sorties. The primary objective of each sortie was to demonstrate a runway touchdown. In addition, shallow (2 degrees) and steep (3 degrees) approaches were flown to qualitatively assess handling qualities during approach and touchdown. Pilot comments were the primary data collected during the touchdown sorties. All approaches were initiated just prior to east lakeshore (approximately 4 mile final) and continued to runway touchdown. At touchdown, the evaluation pilot planned to maintain landing attitude while the safety pilot disengaged the VSS through the rear cockpit paddle switch and initiated a go-around. The approach conditions and pilot comments are listed in table 4.

**Table 4: Touchdown Conditions and Comments**

| Sortie Number & Date | Pilot Background | Wind Conditions (Runway 22) | Approach Type | Pilot comments |
|---|---|---|---|---|
| 10<br>21 Sep | F-15I<br>F-16I | 040/6 | 2.5˚ | Safe touchdown, tiny burble, immediate trip |
| | | | 2.5˚ | Nose up pitch upon touchdown and VSS trip |
| | | | 2.5˚ | Safe touchdown |
| | | | 3.0˚ | Well timed flare and rate required |
| | | | 2.0˚ | No issues. Immediate safety trip at touchdown |
| 11<br>23 Sep | F-16 | 270/8 | 2.5˚ | No problems. Immediate trip at touchdown |
| | | | 2.5˚ | Increased aggressiveness causes small oscillations |
| | | | 2.5˚ | No issues |
| | | | 3.0˚ | Timing is key |
| | | | 2.0˚ | Lack of trim was only issue |
| 12<br>23 Sep | C-17<br>B-2<br>T-38 | 260/12 | 2.5˚ | Small oscillations with fine tuning control |
| | | | 2.5˚ | Similar to F-16, no issues |
| | | | 2.5˚ | Bobble when got behind on flare and made rapid input |
| | | | 3.0˚ | Easy with one smooth pull. When reversing control input, get oscillations |
| | | | 2.0˚ | Small oscillations due to small control reversals |

All touchdowns resulted in an immediate VSS trip upon contact with the runway surface. The safety trips were due to elevator control surface rate limits. They were not unexpected due to the forces associated with runway touchdown acting on system sensors. All runway touchdowns were completed safely, however, pitch oscillations were witnessed and consistent with what was expected due to the results of the previous handling qualities evaluation and simulation results.

## Avenues for Future Research

The DO defined in reference 2 was theorized to control longitudinal flight and produce desired handling throughout the flight envelope without the use of gain scheduling. Ground simulation with the high-fidelity VISTA model, however, resulted in instabilities due to time delays inherent in the system. This led to the use of an „ad-hoc‟ command gain schedule that stabilized the aircraft and allowed the test team to continue with flight test. The test project timeline did not allow for in depth research into possible fixes to the time delay problem. Perhaps there is a control architecture or single gain option that allows the DO to stay true to theory. In addition, if a gain schedule is required, scheduling the gain from an inertial sensor rather than atmospheric sensor may provide adequate performance for aircraft during loss of air data systems. Future research should include researching time delay effects on the DO and methods for dealing with it.

Flight test resulted in amplification of sensor noise and the subsequent pass through of that noise to the control surface. Simulation with sensor noise in the loop reproduced the noise amplification result. The noise was amplified by a factor proportional to the ratio of the „design filter‟ frequency to the „desired dynamics‟ frequency. When the design filter frequency was reduced to a value closer to the desired dynamics frequency, the noise was significantly reduced. Changing the design filter, however, was not within the scope of the test plan and was not flight tested. Future research should include examining the effects of changing the design filter to reduce signal noise while maintaining performance. This can be done primarily with simulation using the high fidelity VISTA model with sensor noise in the loop.

The aircraft response during flight test produced a consistently less damped short period than predicted from simulation. The test plan did not allow for real time adjustment of the „desired dynamics,‟ therefore the test team was required to accept less than ideal flying and handling qualities while completing objectives two and three. The flying and handling qualities could have improved with a higher short period damping ratio. A preliminary look into adjusting the desired dynamics while keeping all else the same produced the result shown in figure 25.

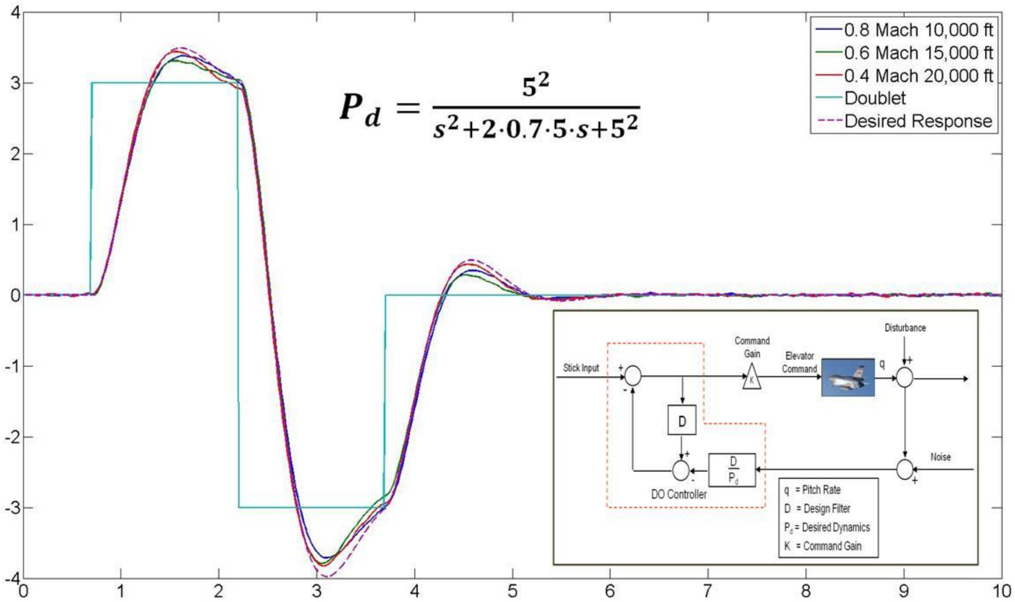


**Figure 25: Pitch Doublet with higher Short Period Damping**

The dashed line labeled „Desired Response" reflects short period damping of 0.5 and is the specification used during flight test. The simulation results represent the aircraft response to a doublet when the DO is commanding a 0.7 damping ratio. Future research should include examining why flight test resulted in a consistently lower damping ratio than simulation. In addition, optimizing the handling qualities could be done by simply adjusting the „desired dynamics" during flight with the VISTA.

The DO was flight tested on the pitch axis only. The lateral directional axes offer avenues for future flight test as well. Additionally, the DO could be incorporated on the variable-stability Learjet operated by Calspan. Applying the DO to the Learjet would allow testers to incorporate multiple axis control while demonstrating the flexibility of the DO by applying the controller to a new airframe with significantly different dynamics than the VISTA.

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# CONCLUSIONS AND RECOMMENDATIONS

The disturbance observer (DO) was used to control longitudinal flight on the Variable stability In-flight Simulator and Test Aircraft (VISTA). The primary project objective was to demonstrate longitudinal flight control. The secondary objective was to demonstrate an approach to 50 feet low approach and the final objective was to demonstrate a touchdown. All objectives were met.

The DO was integrated on the USAF Test Pilot School (TPS) handling qualities simulator and a time delay inherent in the VISTA model acted to cause the DO to command unstable flight. A simple „command gain‟ schedule was applied to the DO architecture that stabilized the aircraft; however, the performance was adversely effected and less consistent throughout the flight envelope. Longitudinal flight control was demonstrated by performing a variety of maneuvers including pitch axis steps, doublets, aerobatics, and free flight. The short period was consistently slower and less damped than the DO defined „desired dynamics.‟ In addition to the reduced performance effects generated by the „ad hoc‟ gain schedule, flight test resulted in consistently lower damping than simulation and desired.

All flight testing revealed a horizontal tail surface „buzz‟ that was a result of pitch rate sensor noise amplification by the disturbance observer. The amplitude of the noise was a function of the difference between the design filter frequency of 26.5 rad/sec and the desired dynamics frequency of 4 rad/sec. Preliminary investigations into reducing the noise concluded that when the design filter frequency was closer in magnitude to the desired dynamics frequency, the noise was significantly reduced. Design filter changes affect the controller performance, and further investigation was found necessary to produce predictable results.

During the buildup to achieve the low approach and touchdown objectives, several handling qualities tasks were conducted. Handling qualities in the approach configuration were affected by the slower and less damped short period frequency and damping ratio. The short period parameters were consistent, however, suggesting that adjusting the „desired dynamics‟ variables to improve the short period response would result in consistent and desired performance. Handling qualities were also negatively affected by actual air turbulence. The aircraft pitch rate sensor passed pitch accelerations from the turbulence to the DO and acted to reduce the controller bandwidth available to the pilot for control. The reduction in bandwidth was noticed during high gain tracking while in turbulence leading to the lowest (poor) pilot-in-the-loop oscillation (PIO) and Cooper-Harper (CH) ratings.

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# REFERENCES


1. Department of Defense. MIL-STD-1797B, *Flying Qualities of Piloted Aircraft*. Feb 2006.

2. Blue, P., D. Odenthal, M Muhler. *Designing Robust Large Envelope Flight Controllers for High-Performance Aircraft.* Guidance, Navigation, and Control Conference and Exibit (Monterey, Ca), August 2002. AIAA 2002-4450.

3. Stevens, Brian L. and Frank L. Lewis. *Aircraft Control and Simulation, Second Edition*. New Jersey: John Wiley & Sons, Incorporated, 2003.

4. Cooper, G. E. and R. P. Harper, Jr. *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*. NASA TN D-5153, April 1969

5. Gray, William. A *Boundary Avoidance Tracking Flight Test Technique for Performance and Workload Assessment*. Society of Experimental Test Pilots, 2007.

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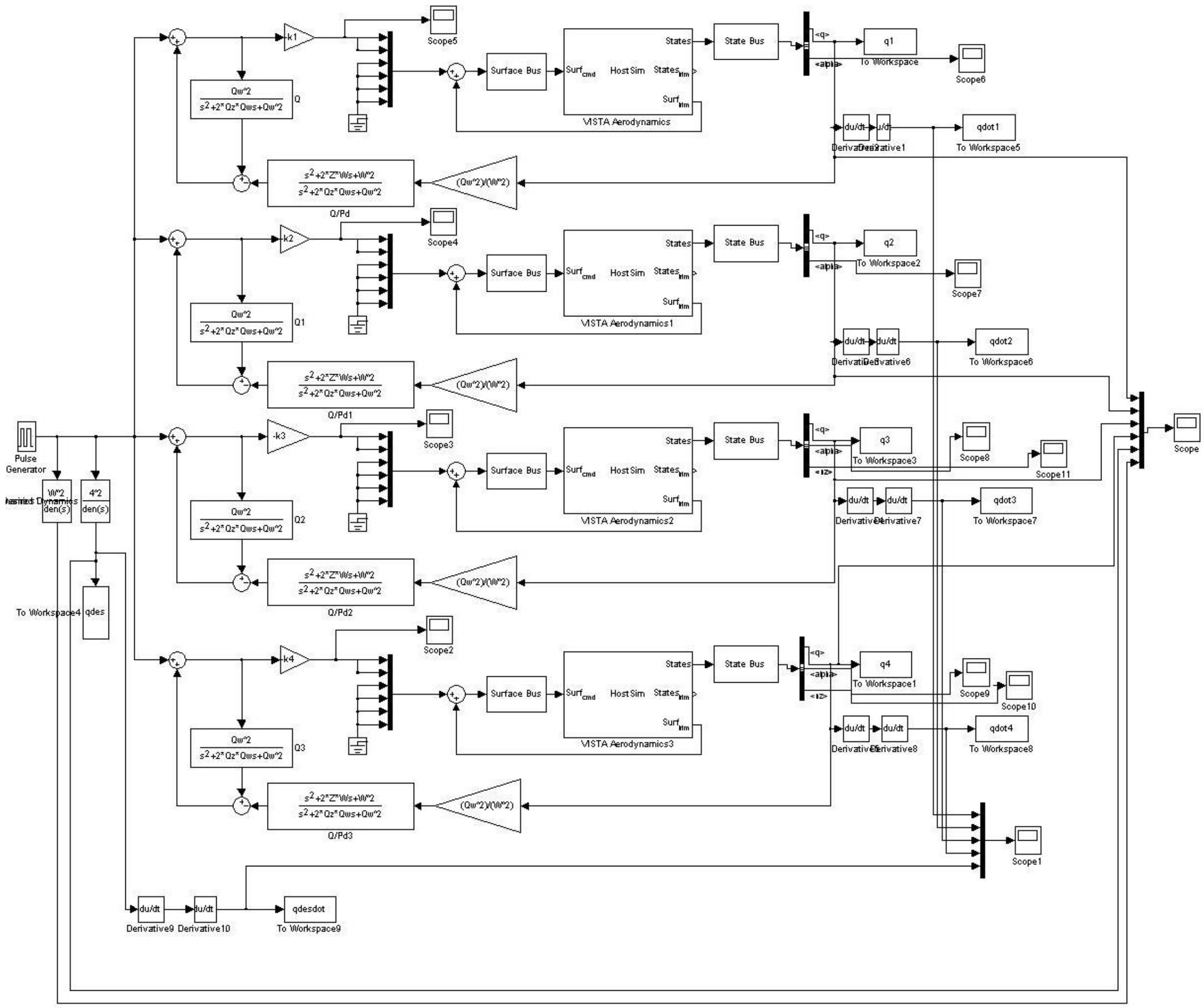
# APPENDIX A – MATLAB® Optimization Function

```
Optimization Function for finding the best Gain 'K' for the Host Sim
Model. 'fminsearch' varies the variables passed to it (design filter,
Qw Qz and command gain K1)in an attempt to minimize the function 'f'
below.  The 'minimize1' simulation is called and run with the three
variables.  The output of the simulation 'qdesdot' and 'qdot1' are used
in the function 'f'.  'fminsearch' continues to run until the short
period response in the simulation is close to the desired response. The
design filter variables and command gain are output at the end of the
search.

close; clc; clear;
warning off
W = 4;
Z = .5;

Qw = 26.2;
Qz = .5;
k1 = .1;

x0=[.1 26.2 .5];
[x fval] = fminsearch(@(x) finder1(x(1), x(2), x(3)),x0);


function f = finder1(k1, Qw, Qz)

assignin('base', 'k1', k1);
assignin('base', 'Qw', Qw);
assignin('base', 'Qz', Qz);
sim minimize1
qdes=qdes.signals.values(10:500);
q1=q1.signals.values(10:500);
qdesdot=qdesdot.signals.values(10:500);
qdot1=qdot1.signals.values(10:500);
assignin('base', 'qdesdot', qdesdot);
assignin('base', 'qdot1', qdot1);
assignin('base', 'qdes', qdes);
assignin('base', 'q1', q1);

f =((qdesdot-qdot1).^2);
f = sum(f)
```

Simulink® model for design filter and command gain optimization:



# APPENDIX B – ACRONYM LIST

AFFTC – Air Force Flight Test Center
AFFTCI – Air Force Flight Test Center Instruction
AOA – Angle of Attack
CH – Cooper Harper
DFLCC – Digital Flight Control Computer
D- Design Filter
DO – Disturbance Observer
FTT – Flight Test Technique
HUD – Heads Up Display
IP – Instructor Pilot
JON – Job Order Number
KCAS – Knots Calibrated Air Speed
K – Command Gain
KIAS – Knots Indicated Air Speed
MSL – Mean Sea Level
MURDOC – Multi Use Rate Disturbance Observer Controller
PA – Pressure Altitude (if adjacent to number), Powered Approach (otherwise)
PIO – Pilot In the loop Oscillation
PTI – Programmable Test Input
q – Pitch Rate
RTO – Responsible Test Organization
SRB – Safety Review Board
TIM – Technical Information Memorandum
TMP – Test Management Project
TPS – Test Pilot School
VISTA - Variable stability In-flight Simulator Test Aircraft
VSS – VISTA Simulation System
WUT – Wind Up Turn

# APPENDIX C – FULL PAGE PLOTS

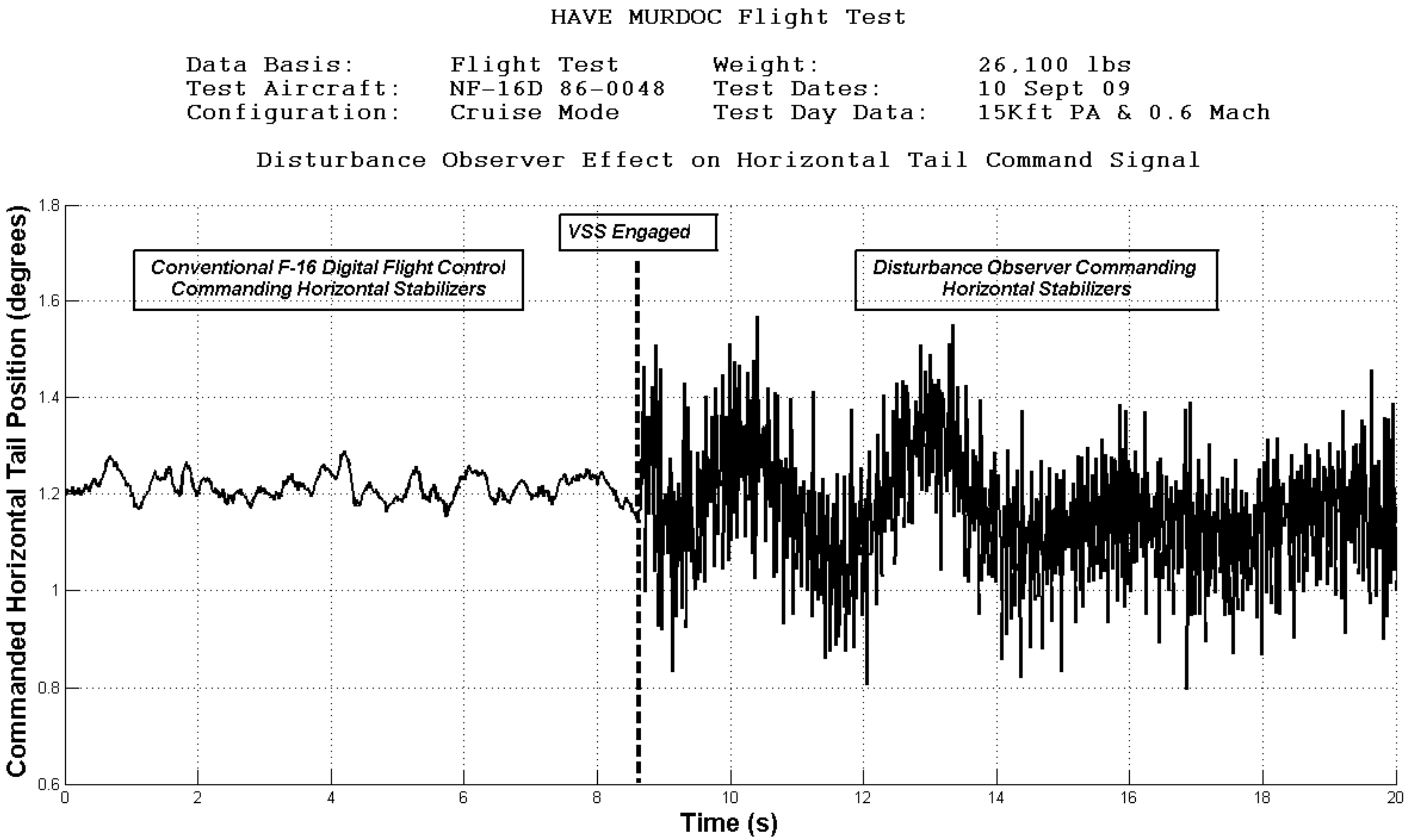



**Figure C-1: Horizontal Tail Command Signal**

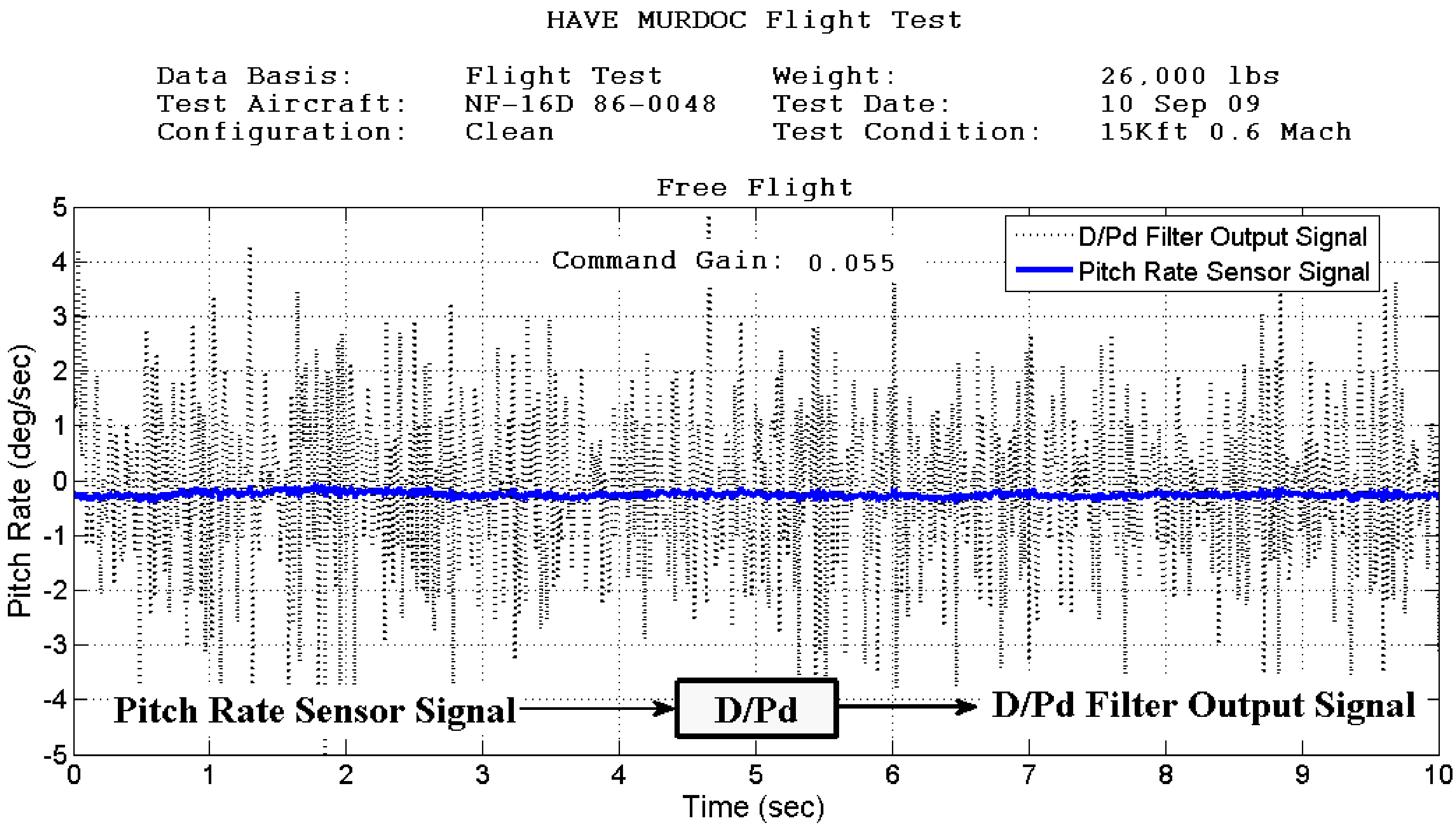



**Figure C-2: DO Pitch Rate Sensor Noise Amplification**

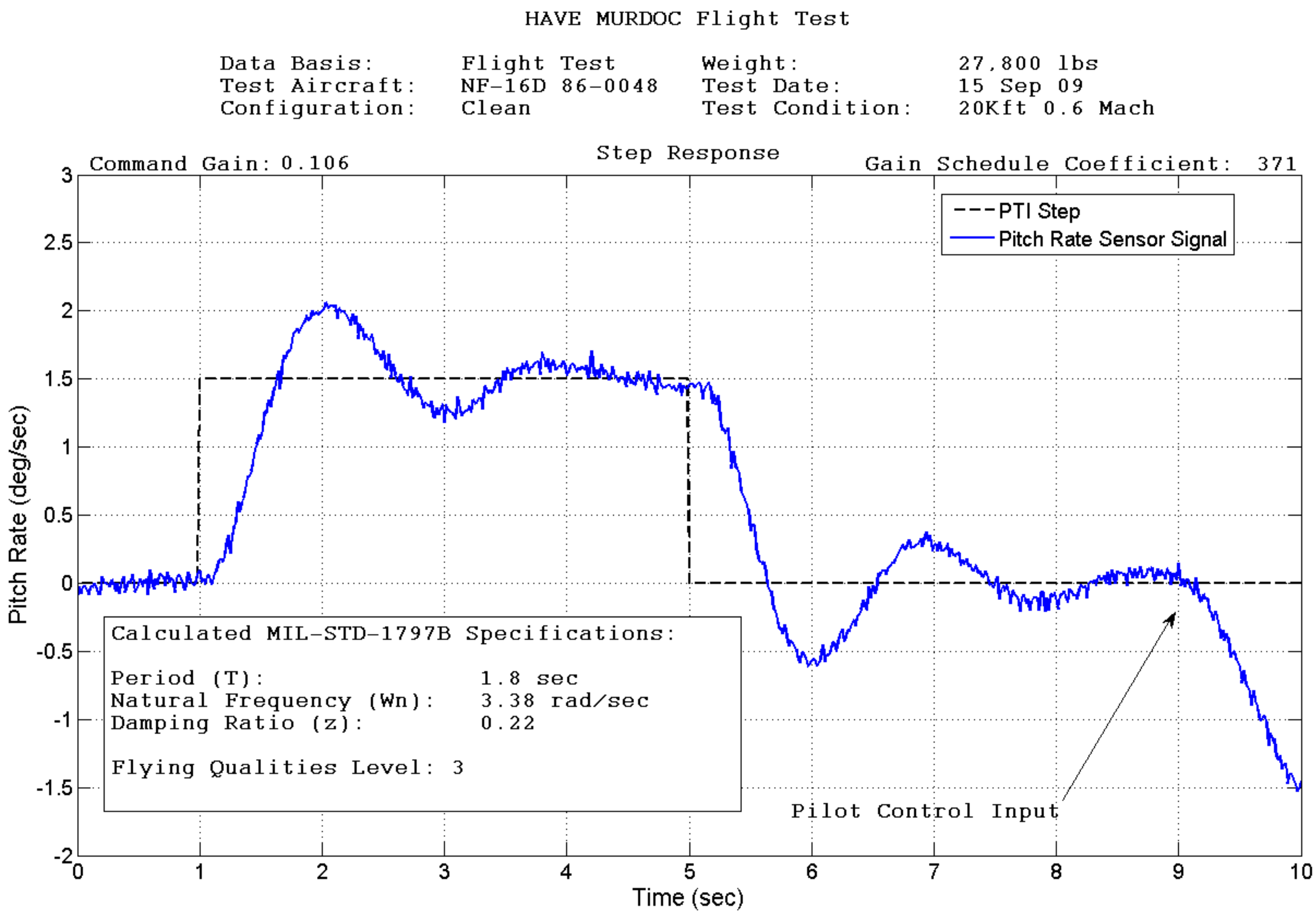



**Figure C-3: Short Period Response to a PTI Step (20K, 0.6 Mach)**

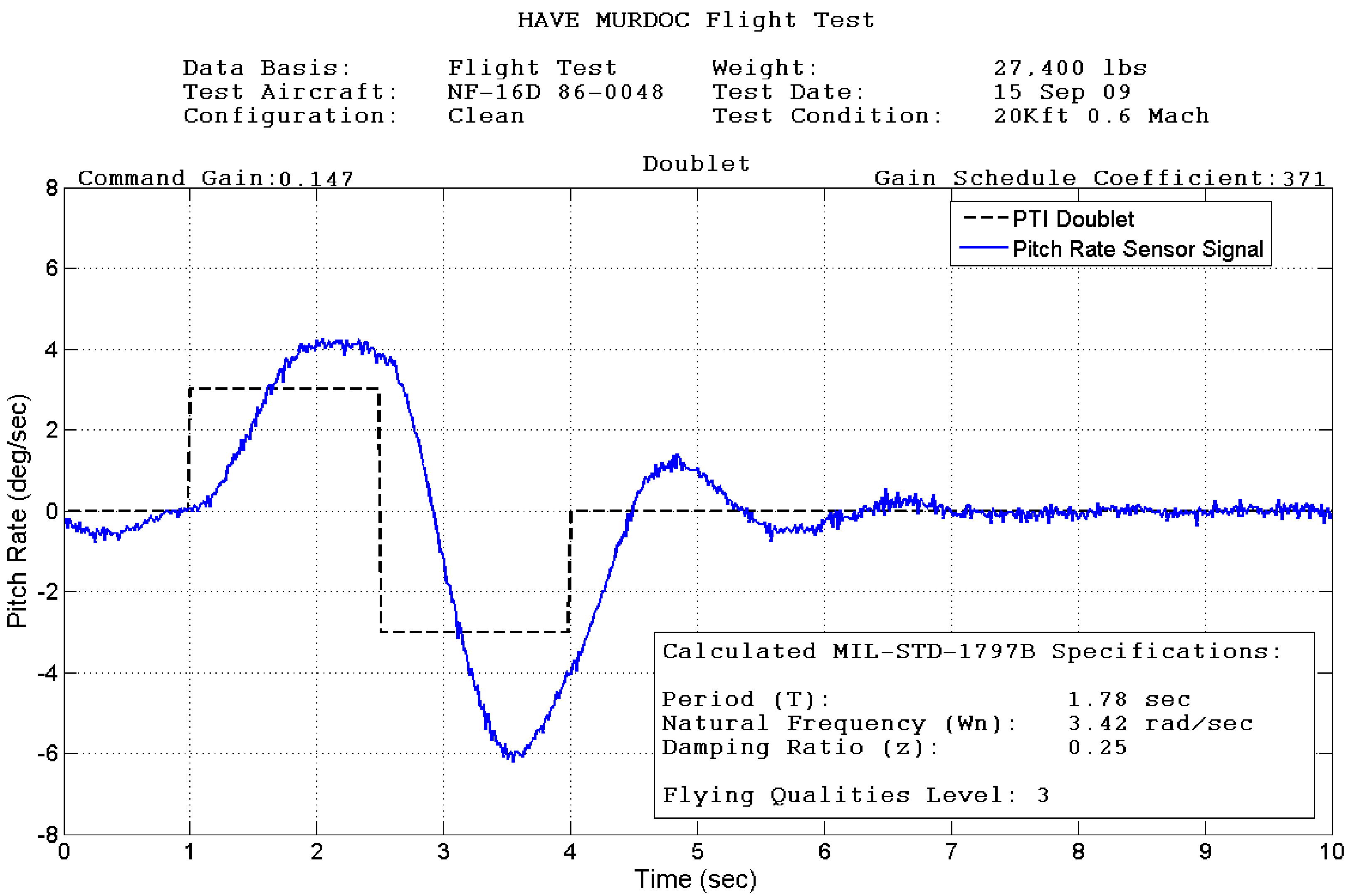



**Figure C-4: Short Period Response to a PTI Doublet (20K, 0.6 Mach)**

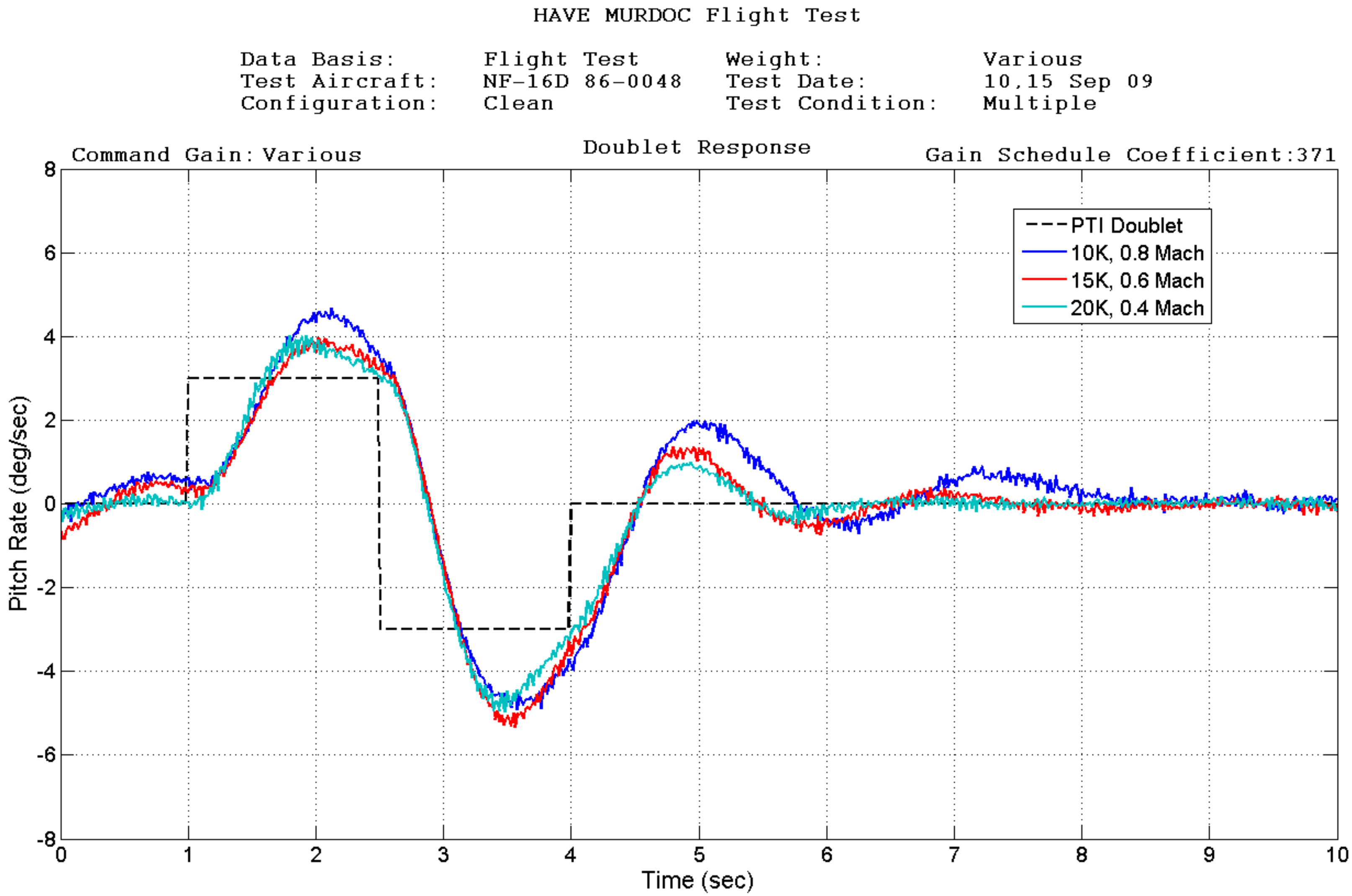



**Figure C-5: Doublet Comparison at Three Different Conditions**

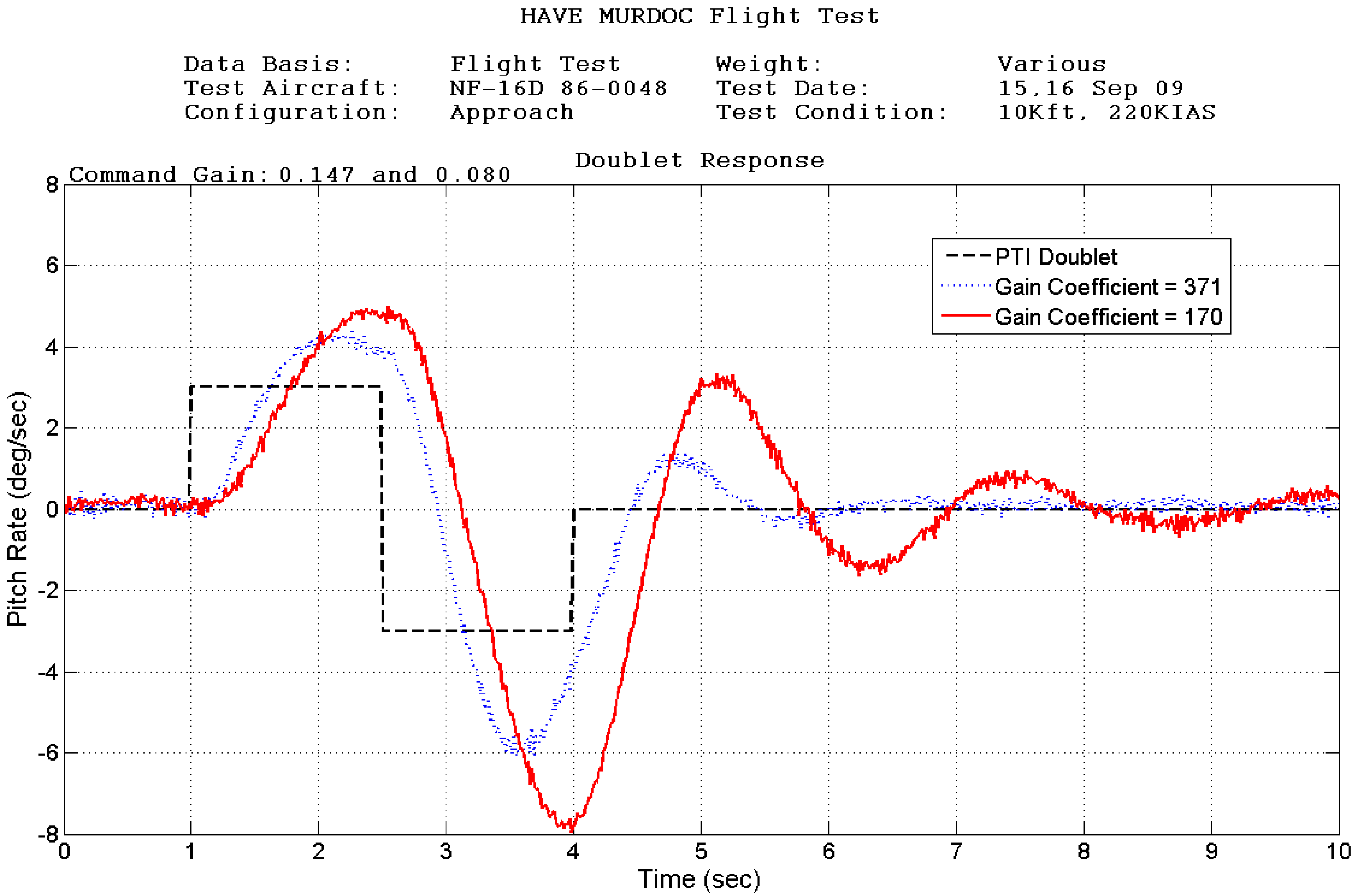



**Figure C-6: Command Gain Effect on PTI Doublet**

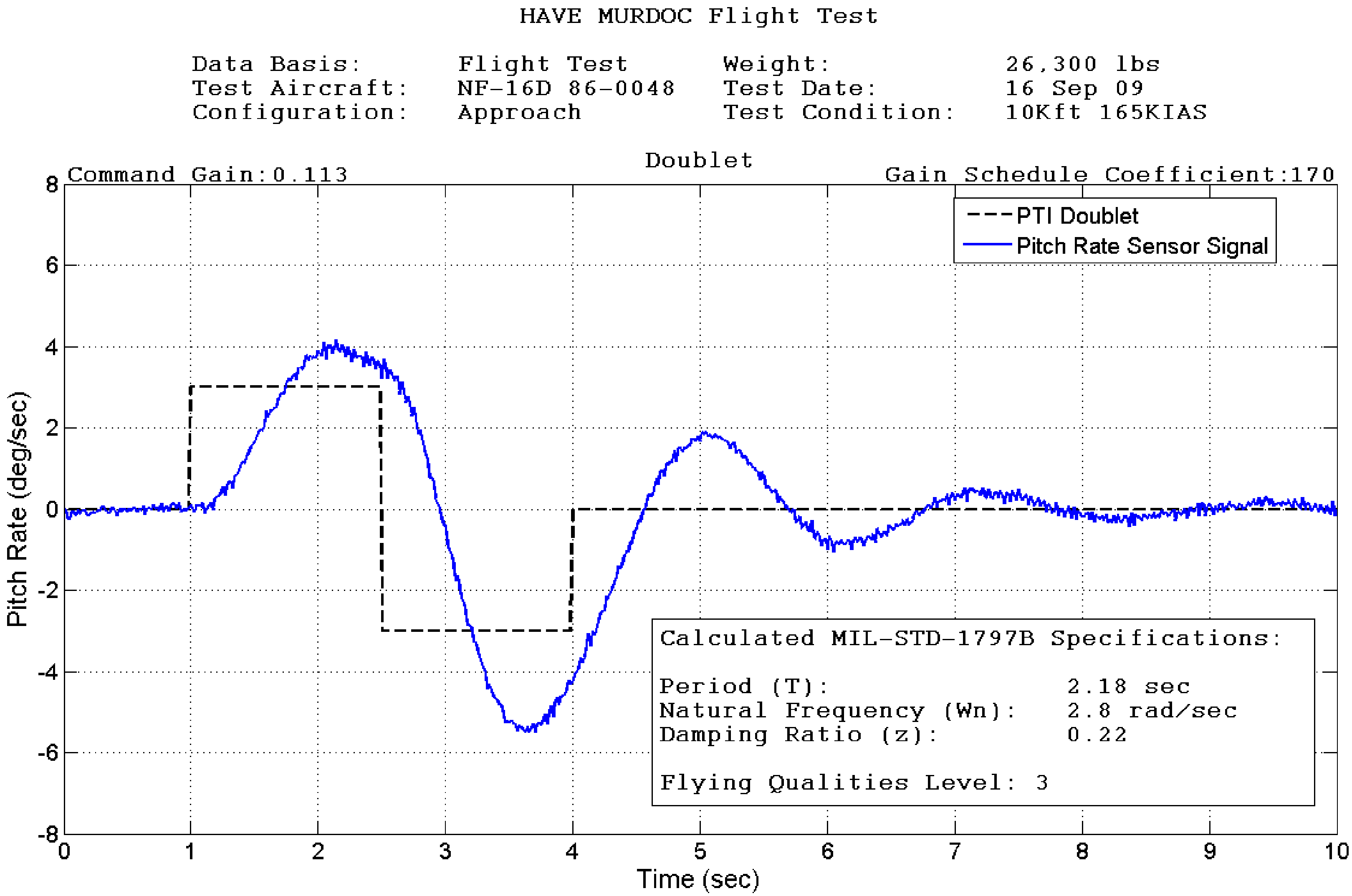



**Figure C-7: Powered Approach Doublet Response**

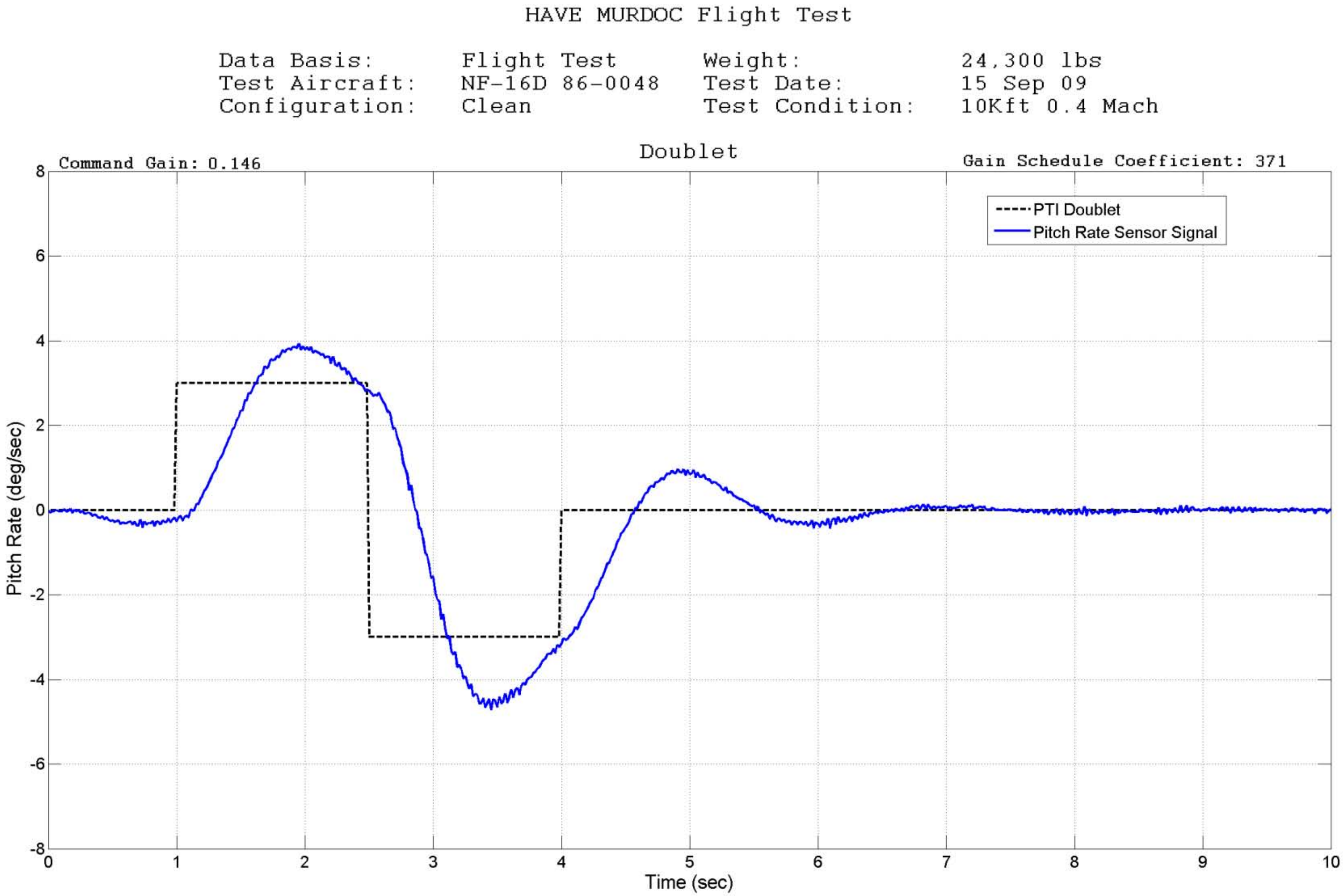



**Figure C-8: Doublet (10K, 0.4 Mach)**

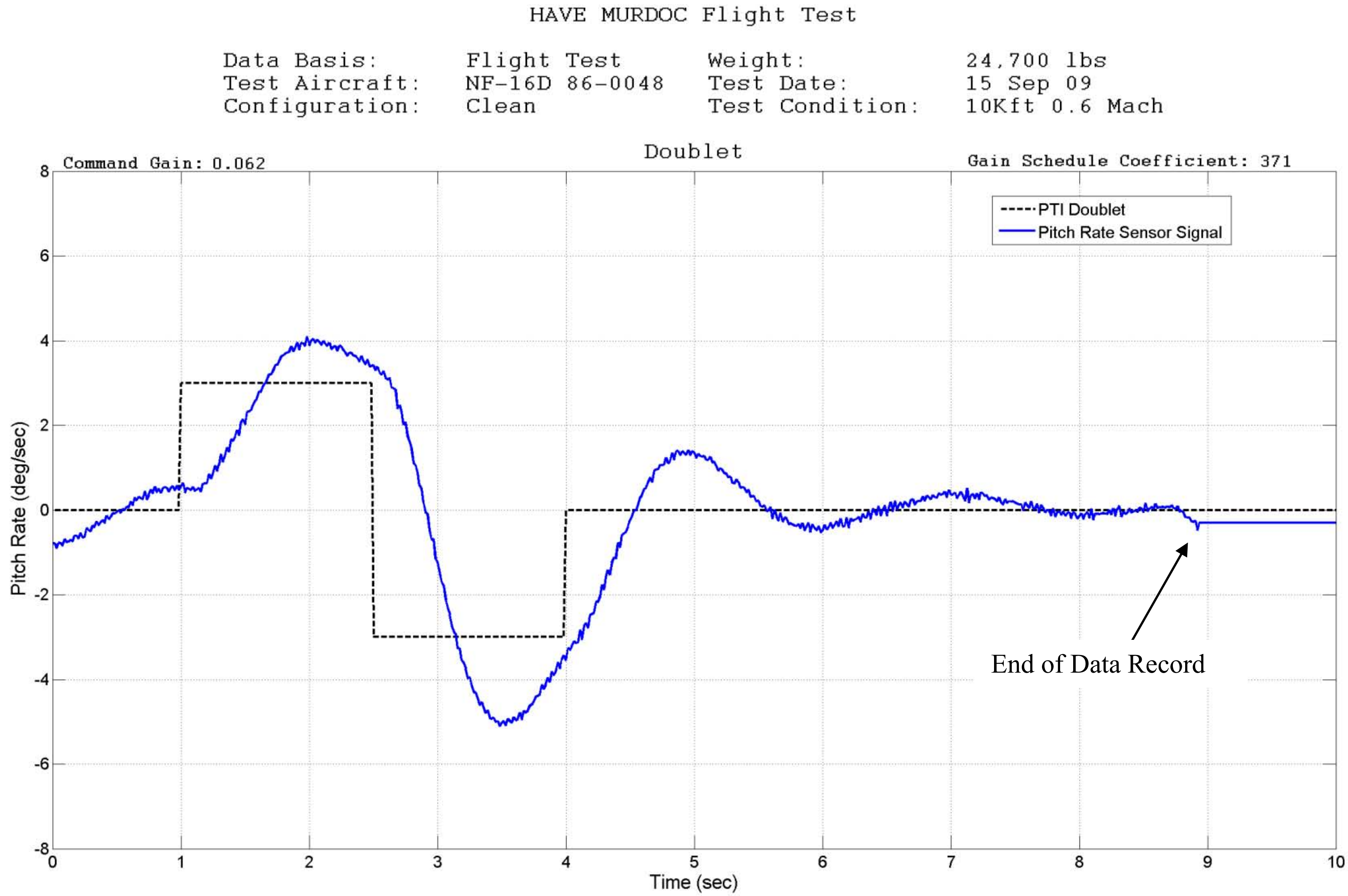



**Figure C-9: Doublet (10K, 0.6 Mach)**

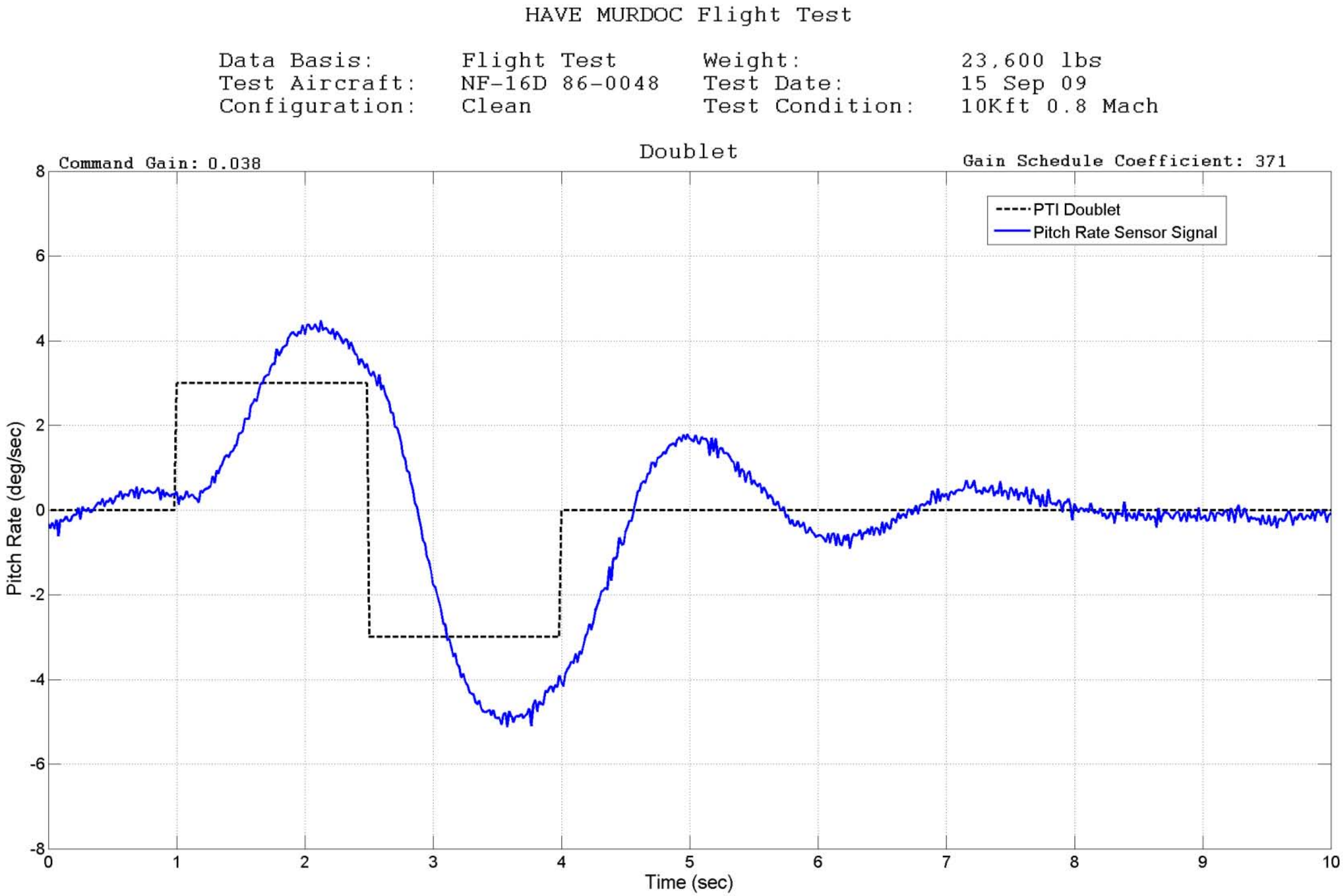



**Figure C-10: Doublet (10K, 0.8 Mach)**

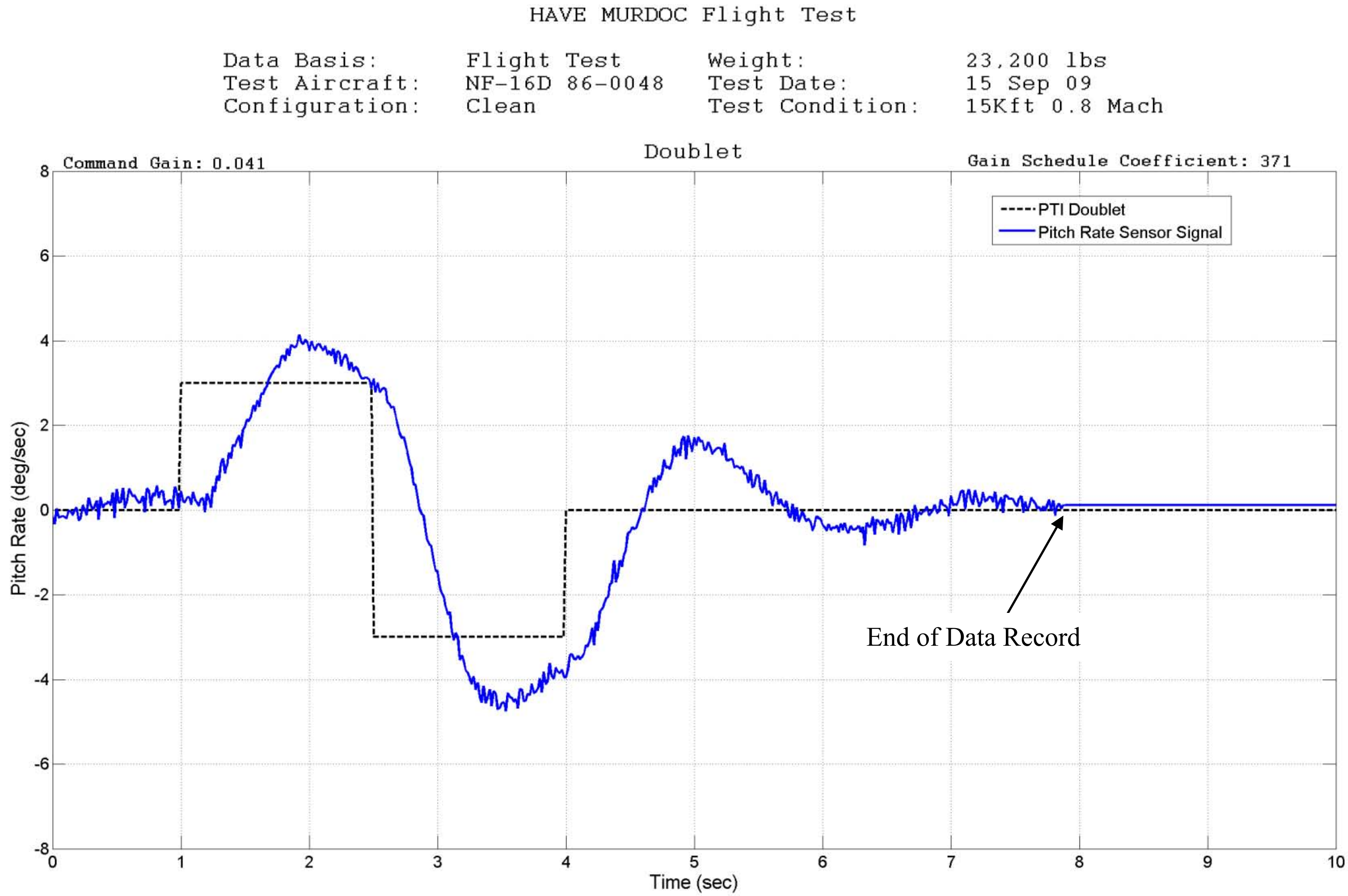



**Figure C-11: Doublet (15K, 0.8 Mach)**

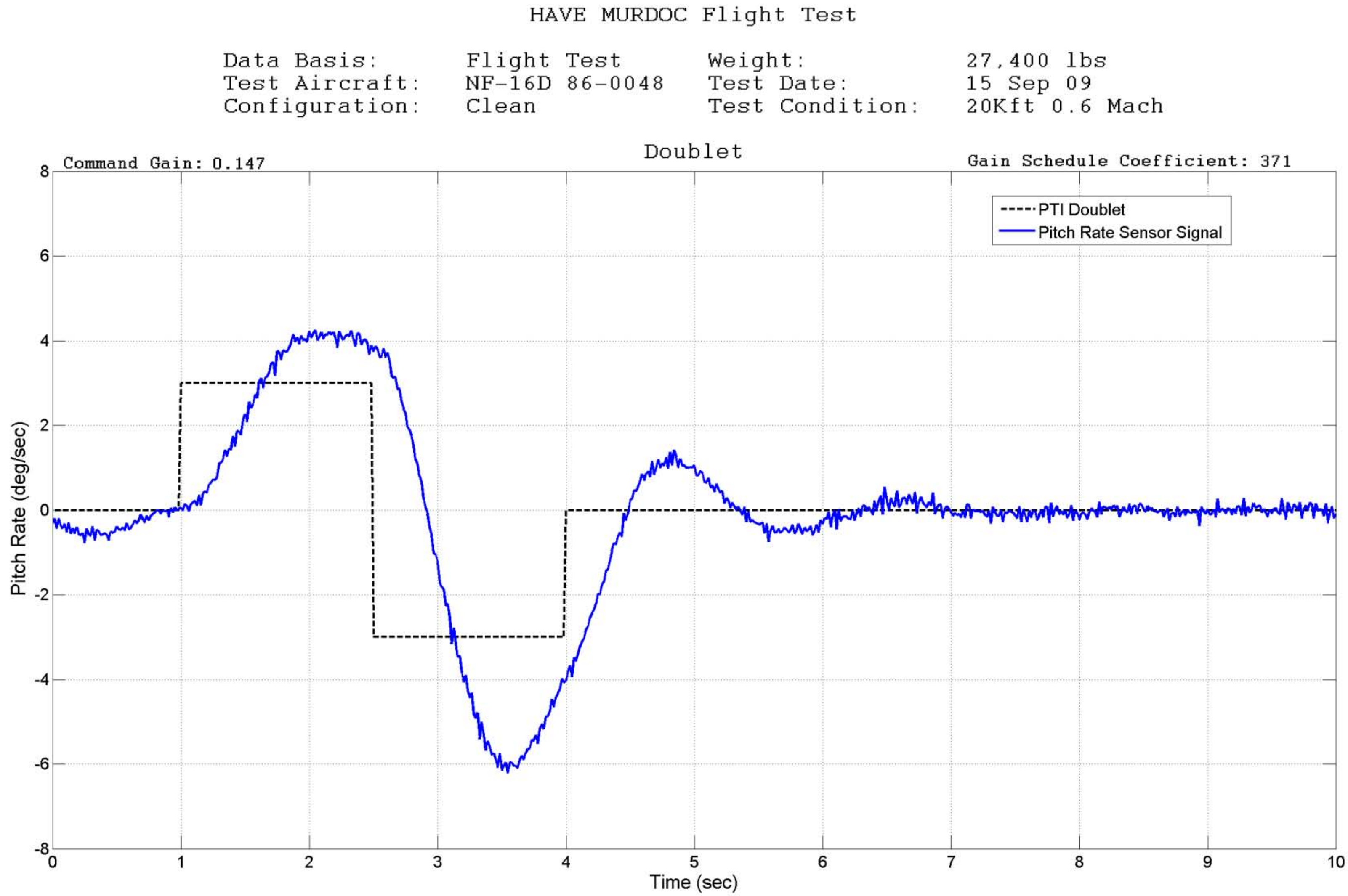



**Figure C-12: Doublet (20K, 0.6 Mach)**

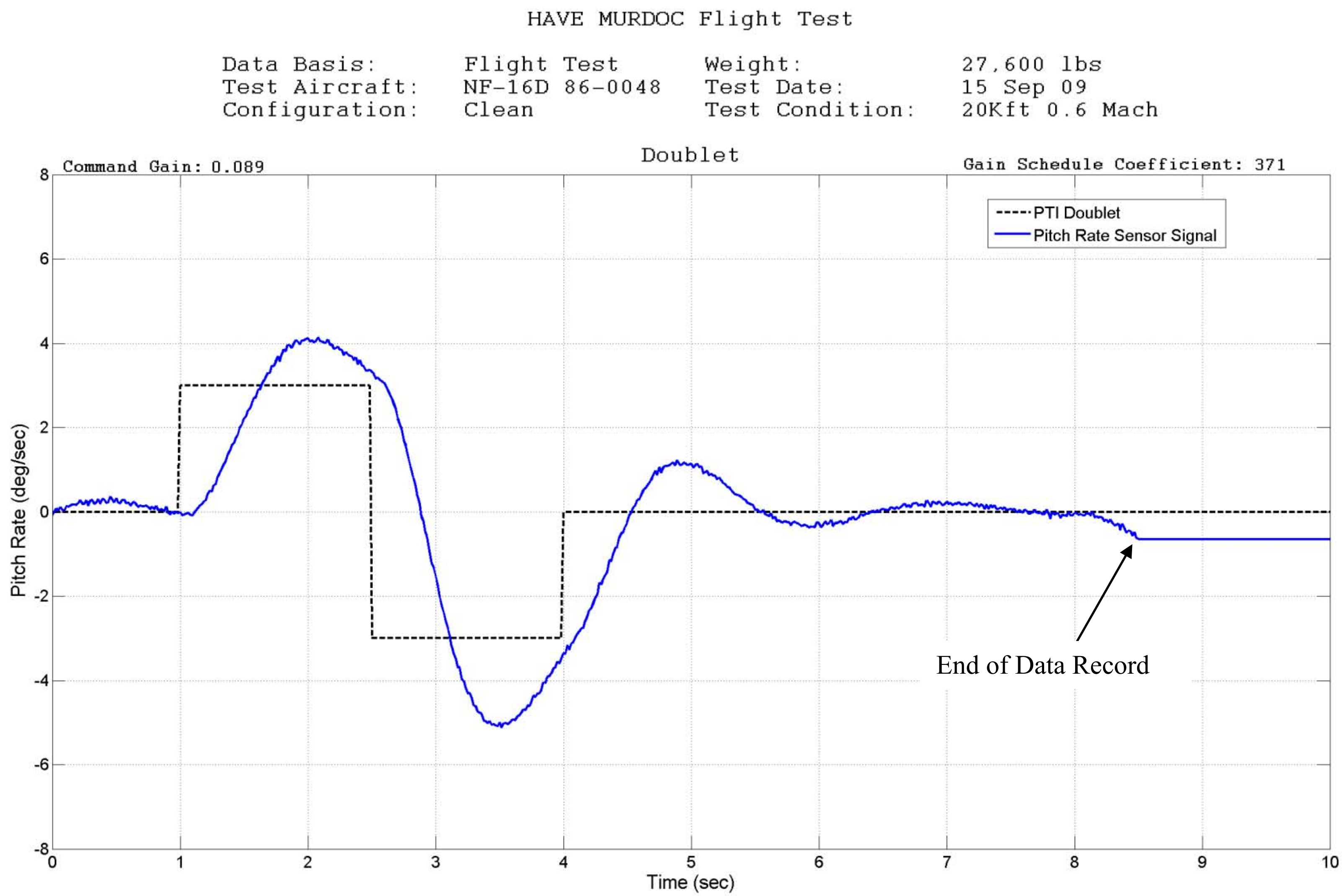



**Figure C-13: Doublet (20K, 0.6 Mach)**

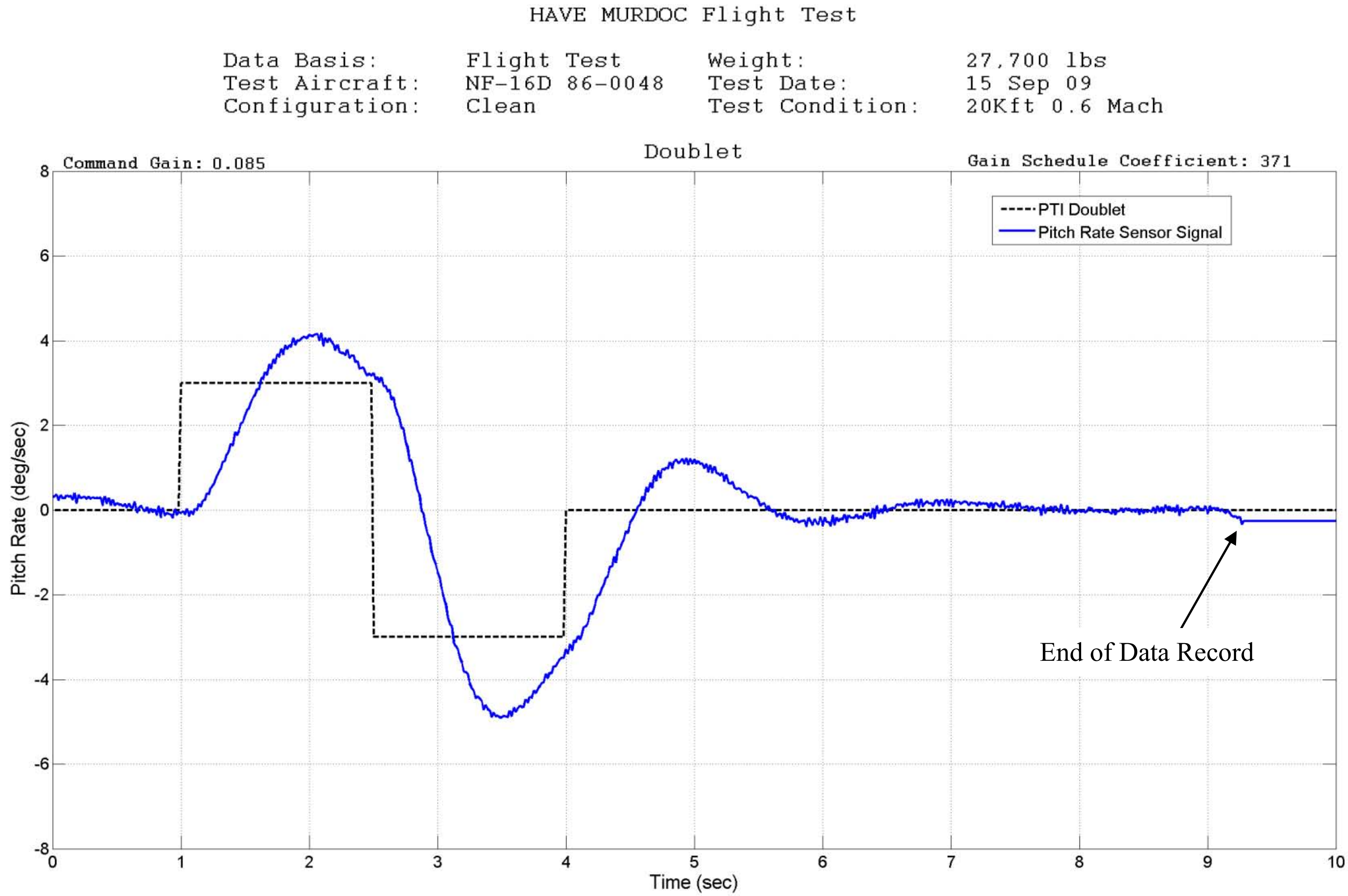



**Figure C-14: Doublet (20K, 0.6 Mach)**

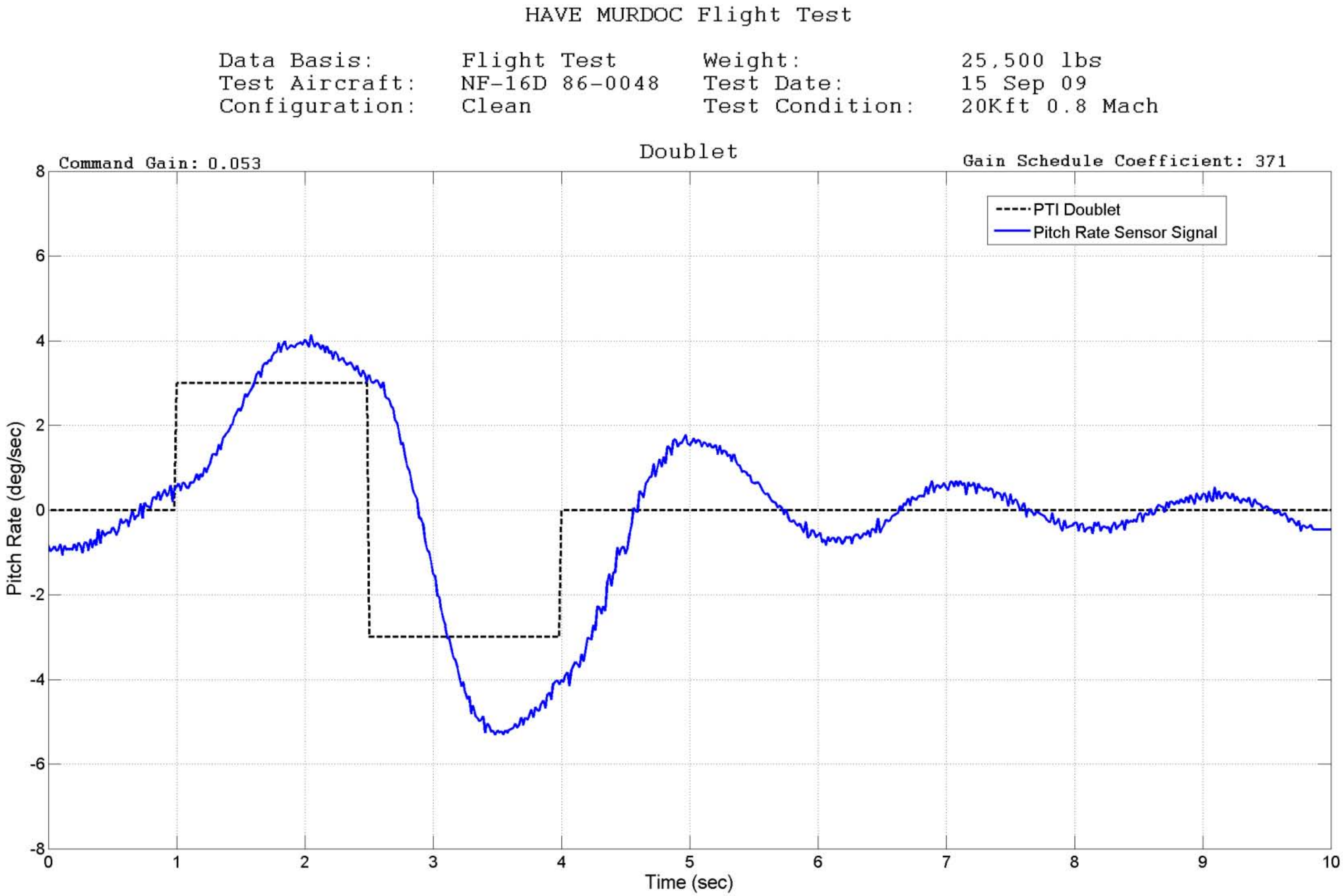



**Figure C-15: Doublet (20K, 0.8 Mach)**

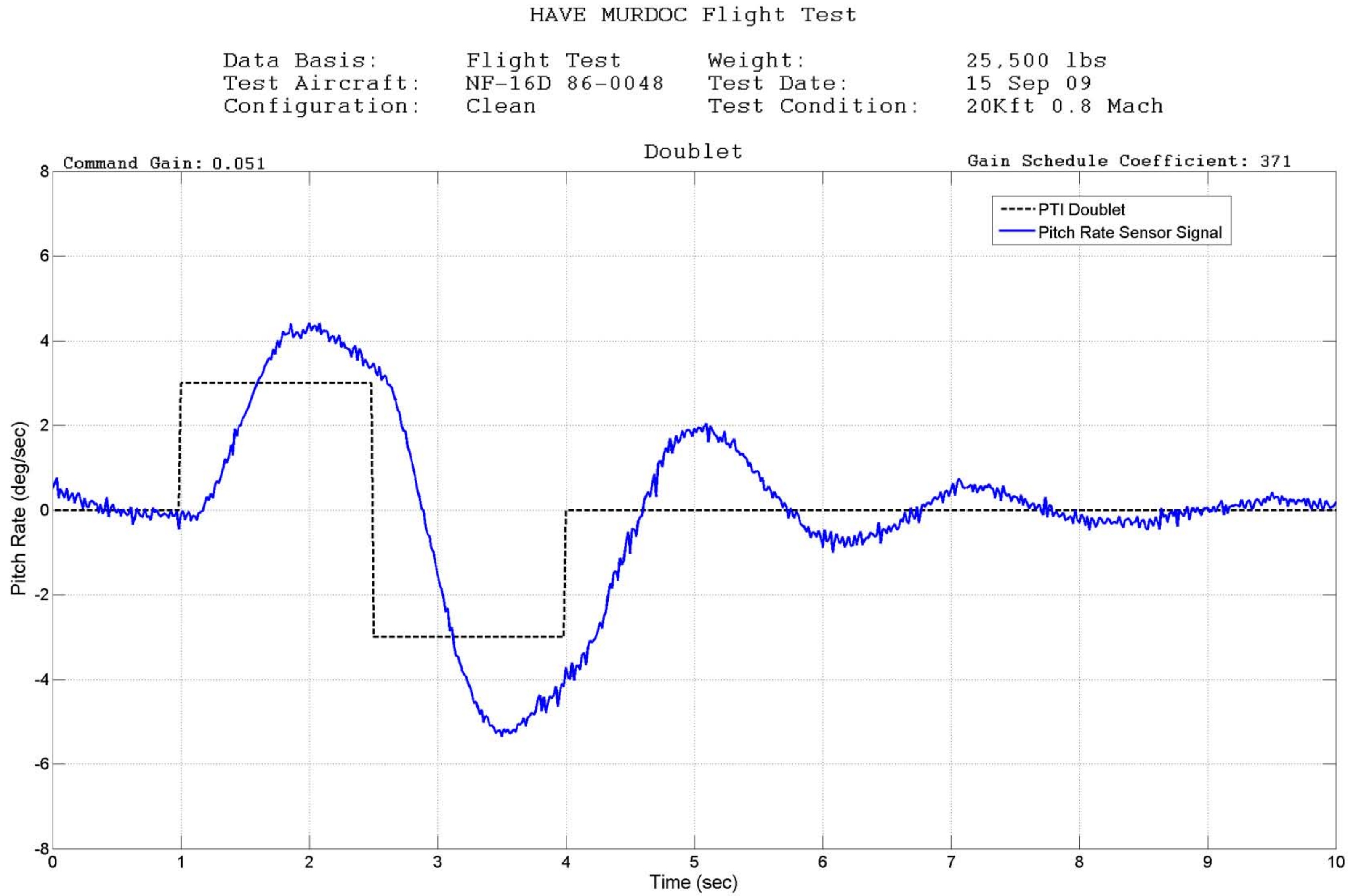



**Figure C-16: Doublet (20K, 0.8 Mach)**

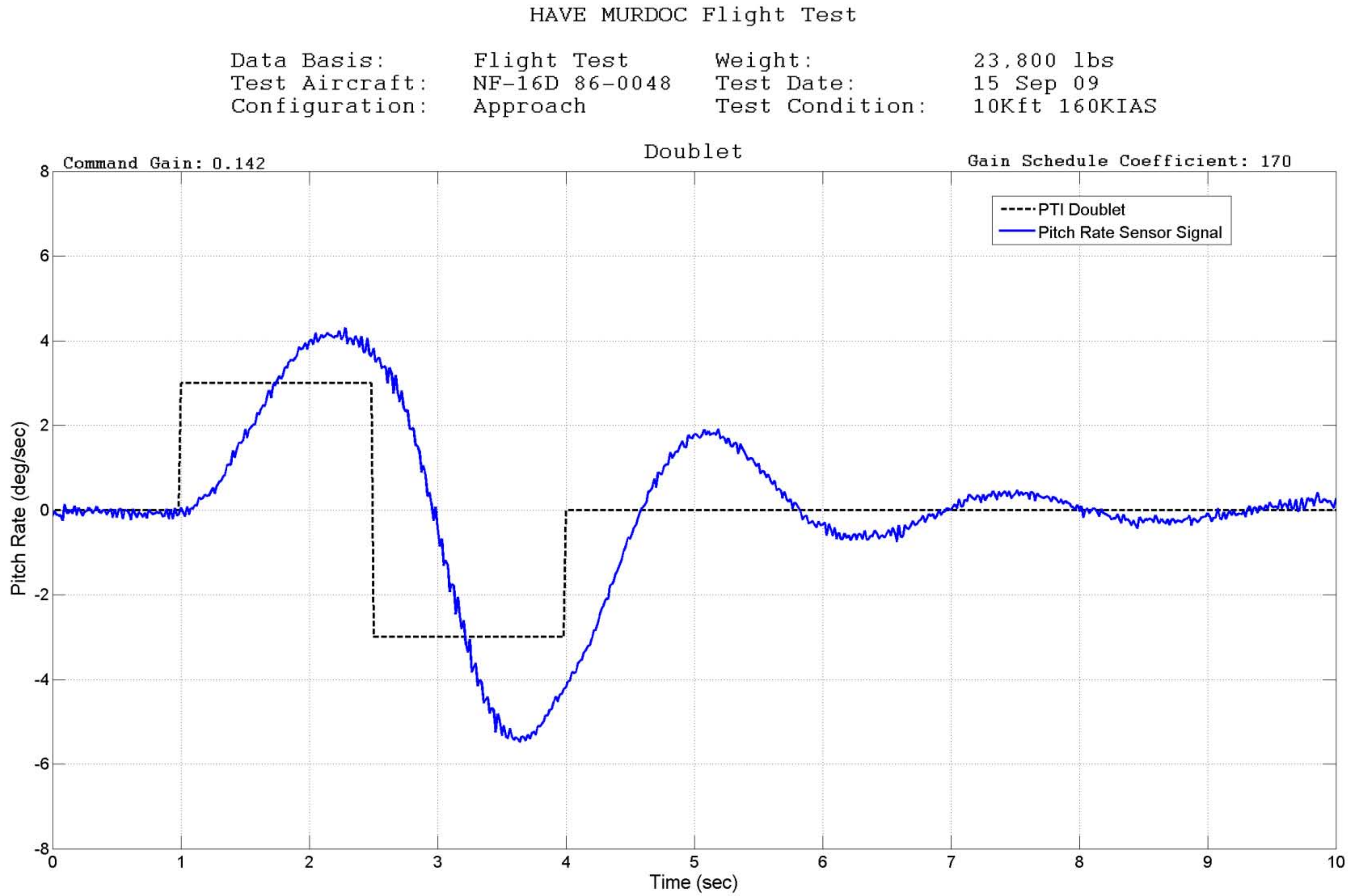



**Figure C-17: Doublet (10K, 160KIAS)**

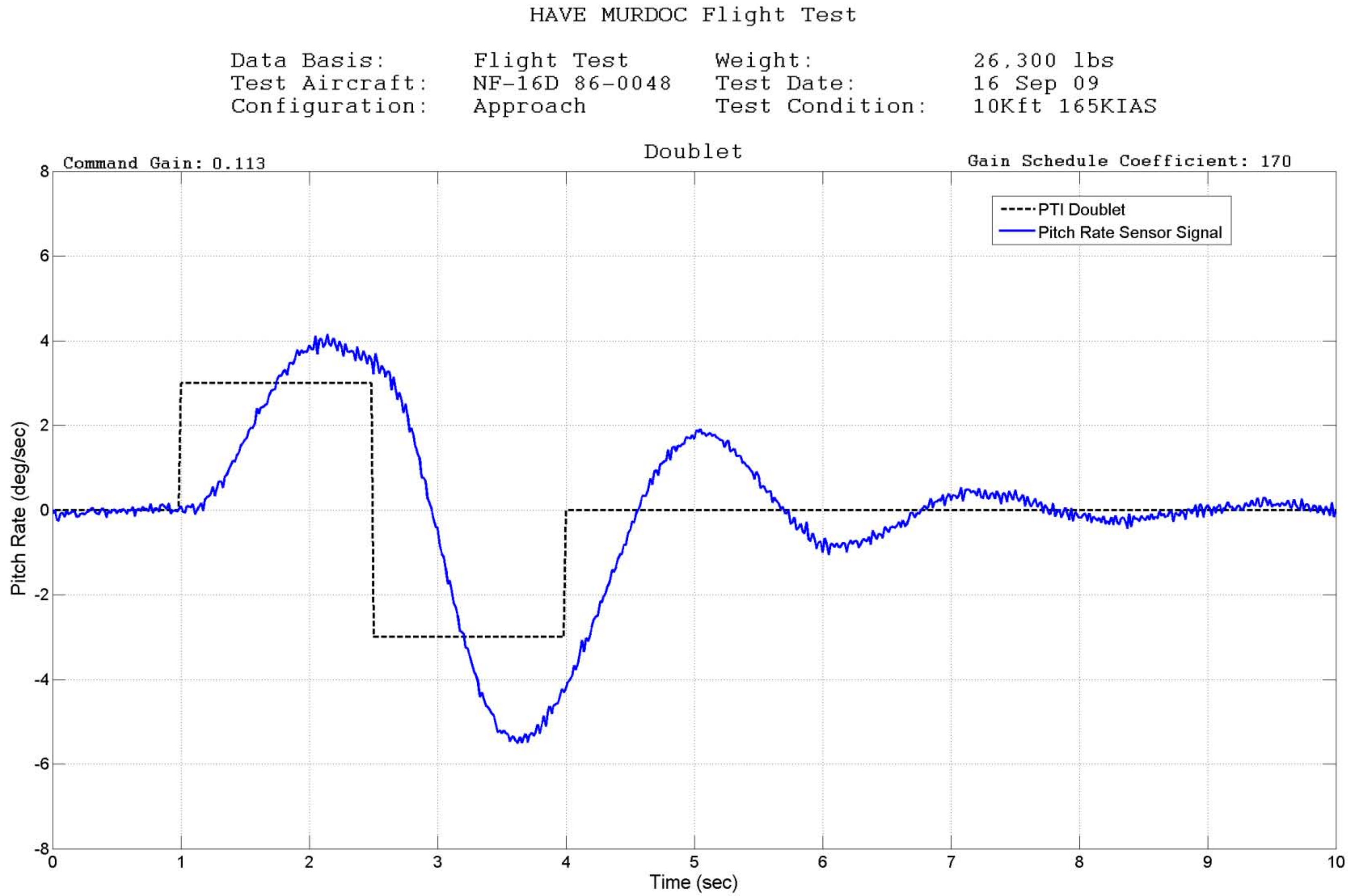



**Figure C-18: Doublet (10K, 165KIAS)**

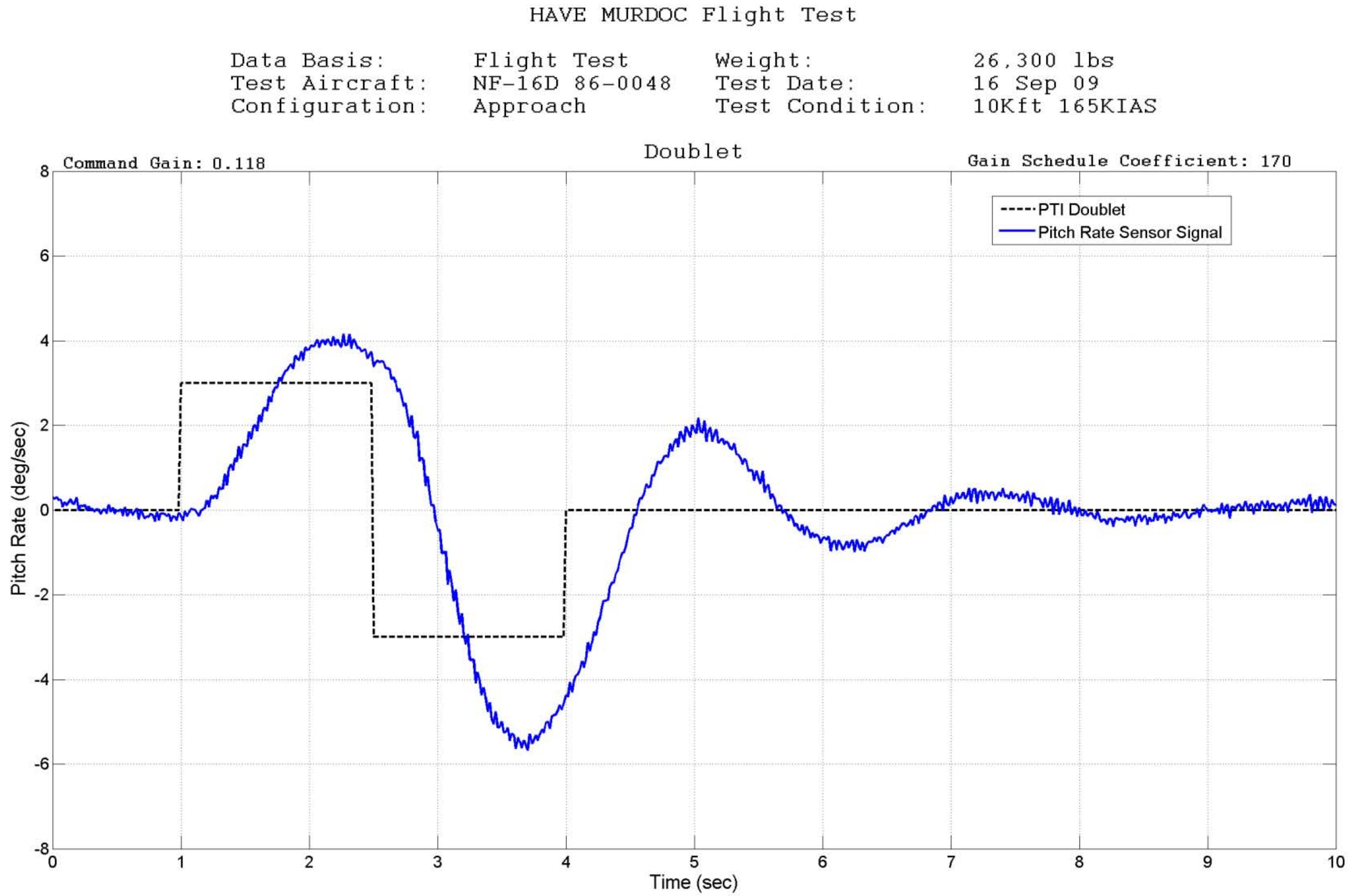



**Figure C-19: Doublet (10K, 165KIAS)**

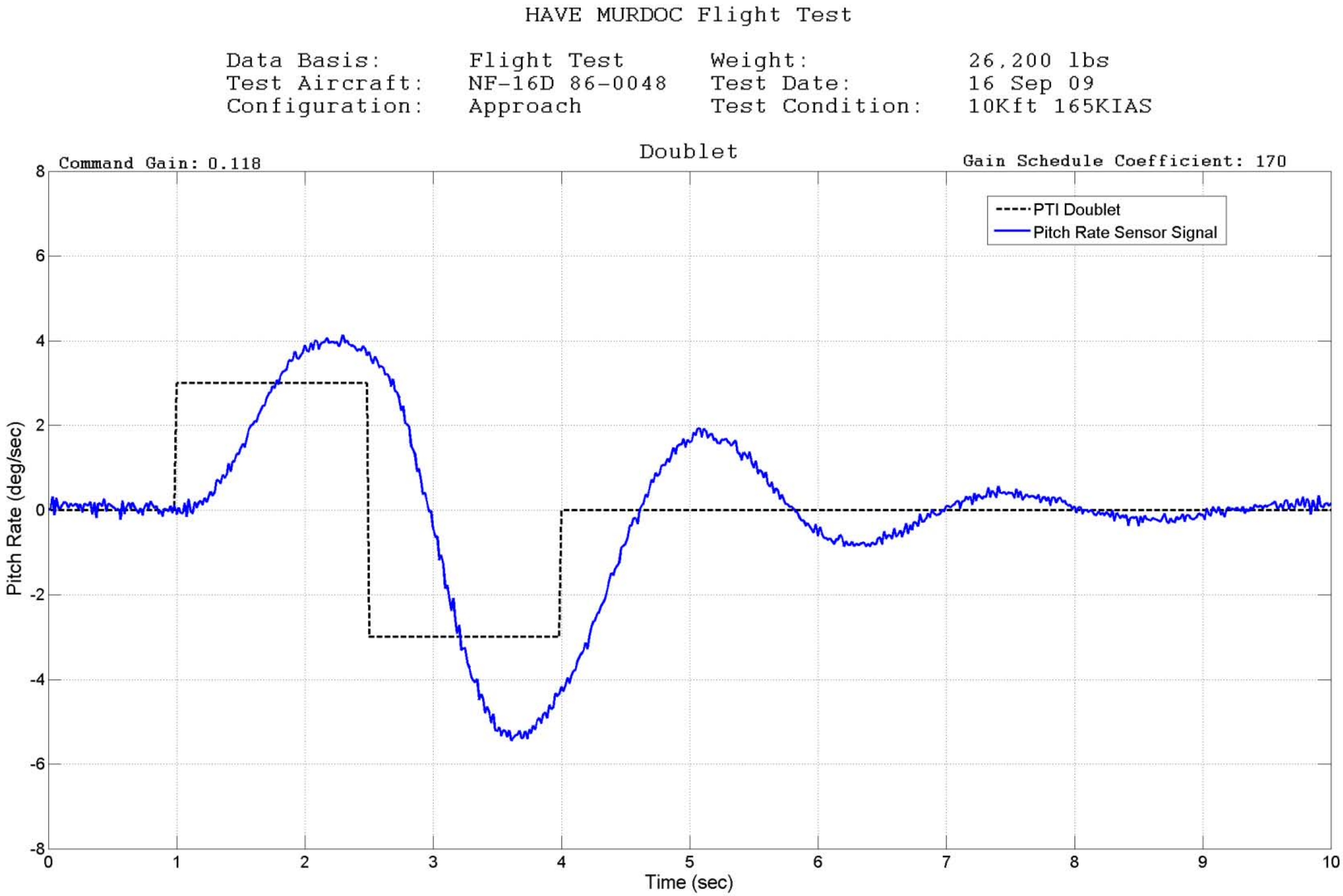



**Figure C-20: Doublet (10K, 165KIAS)**

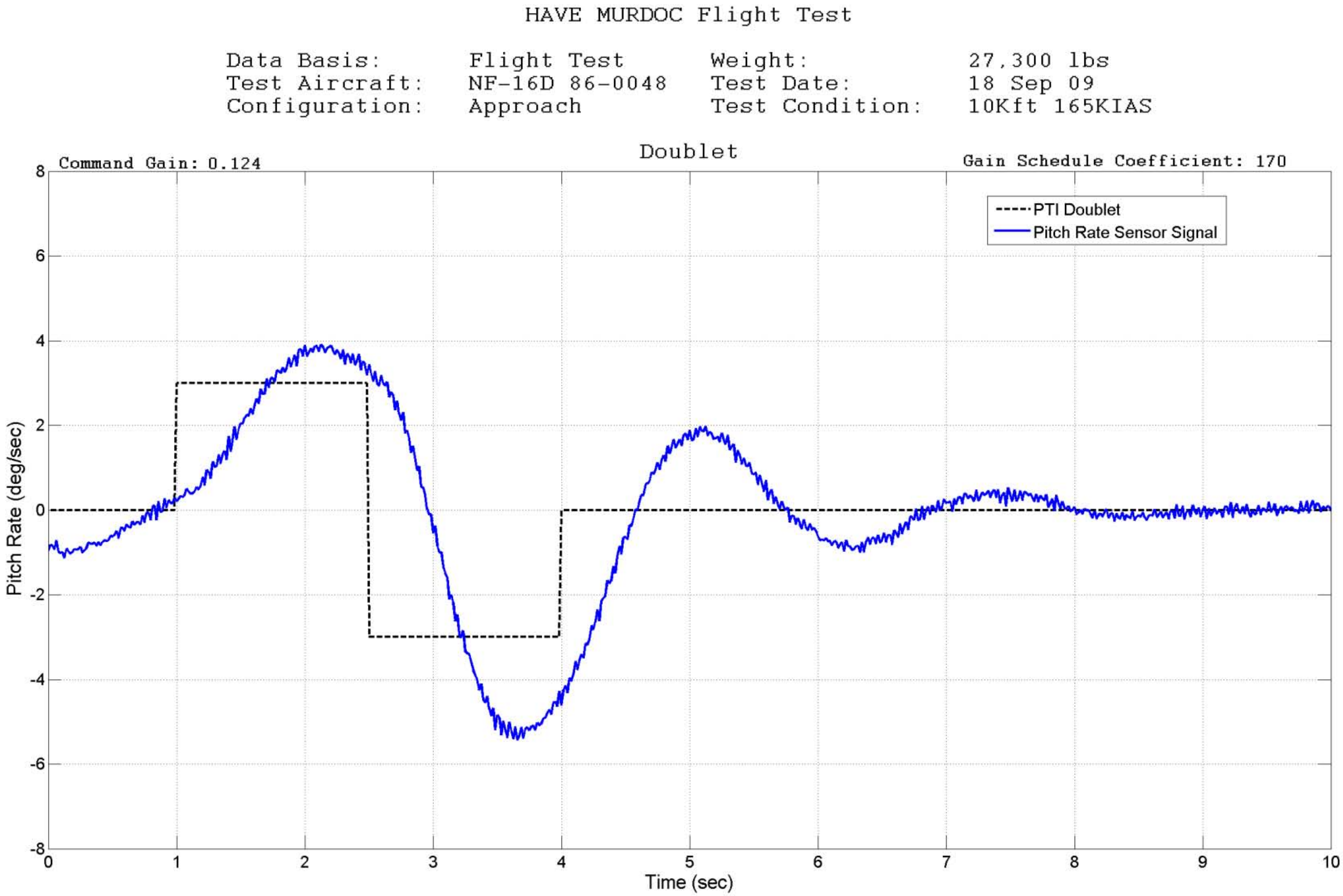



**Figure C-21: Doublet (10K, 165KIAS)**

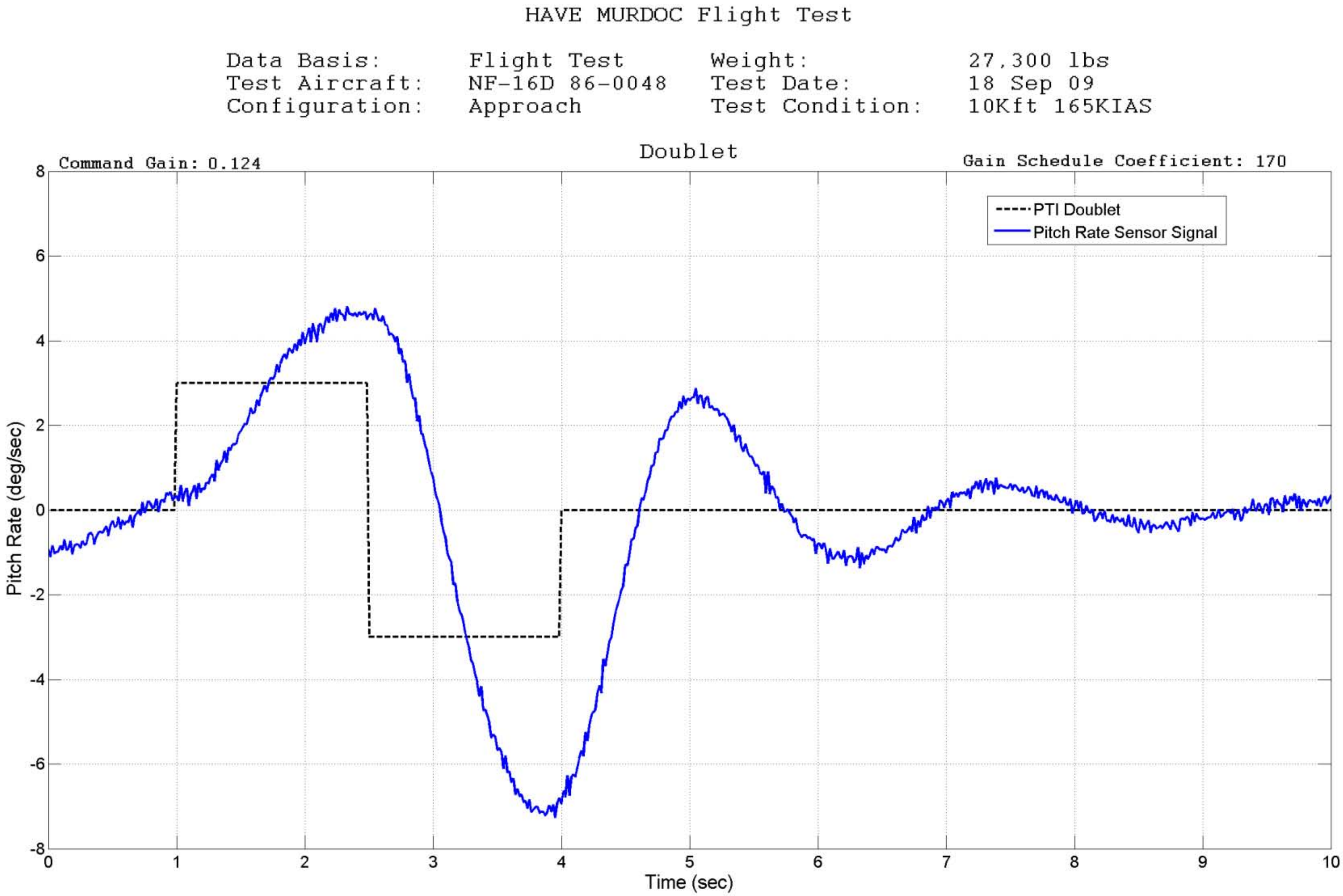



**Figure C-22: Doublet (10K, 165KIAS)**

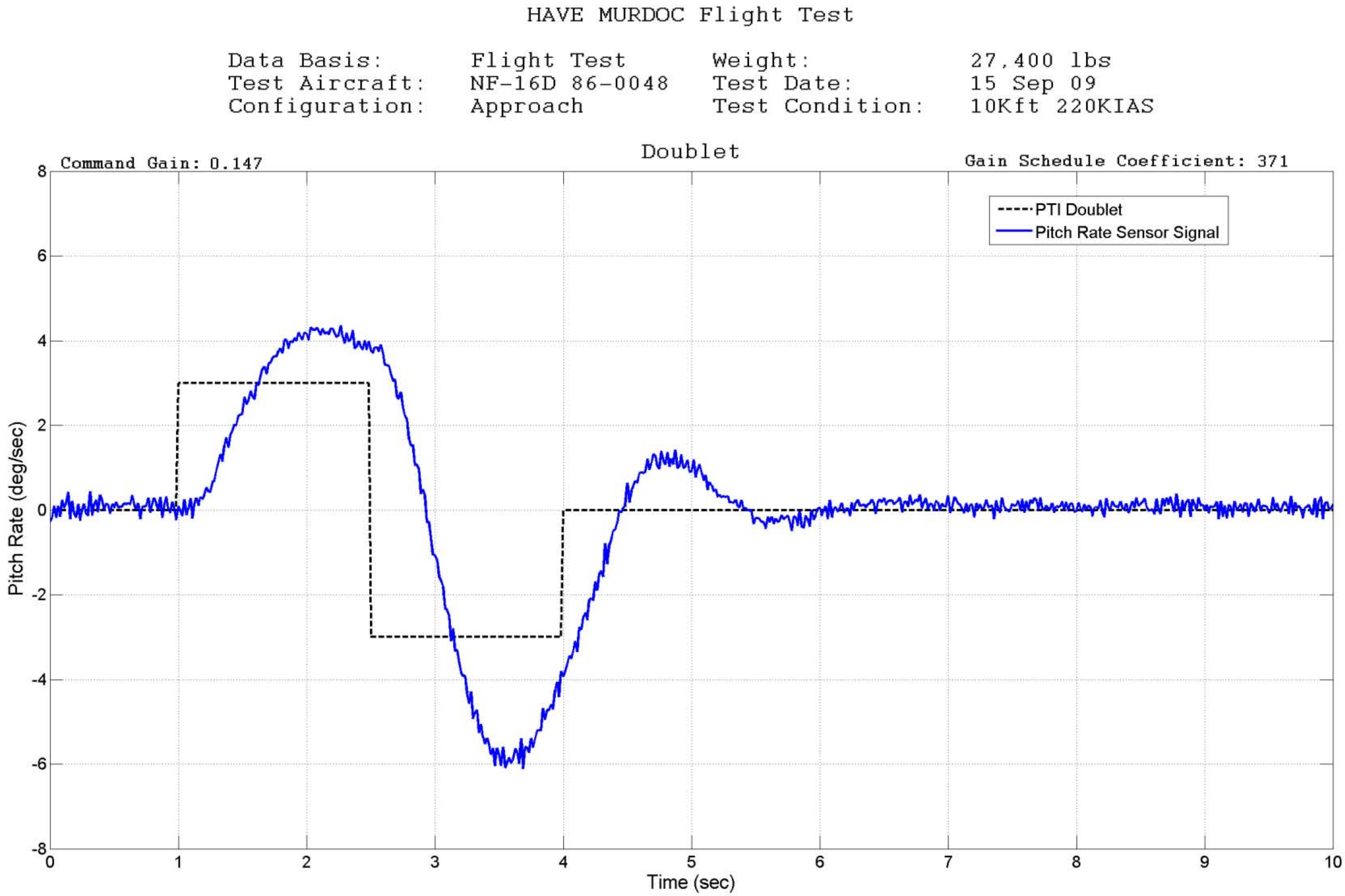



**Figure C-23: Doublet (10K, 220KIAS)**

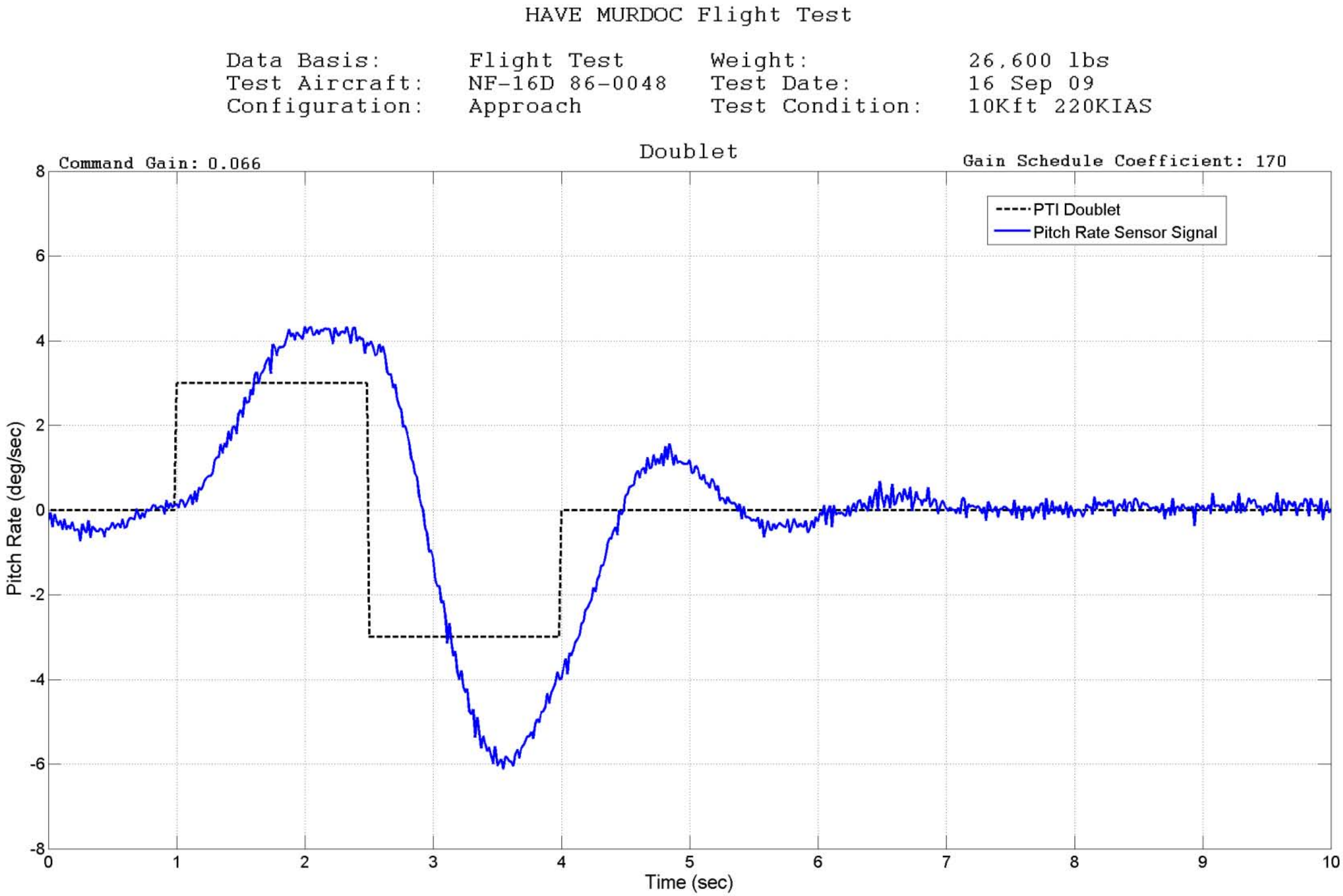



**Figure C-24: Doublet (10K, 220KIAS)**

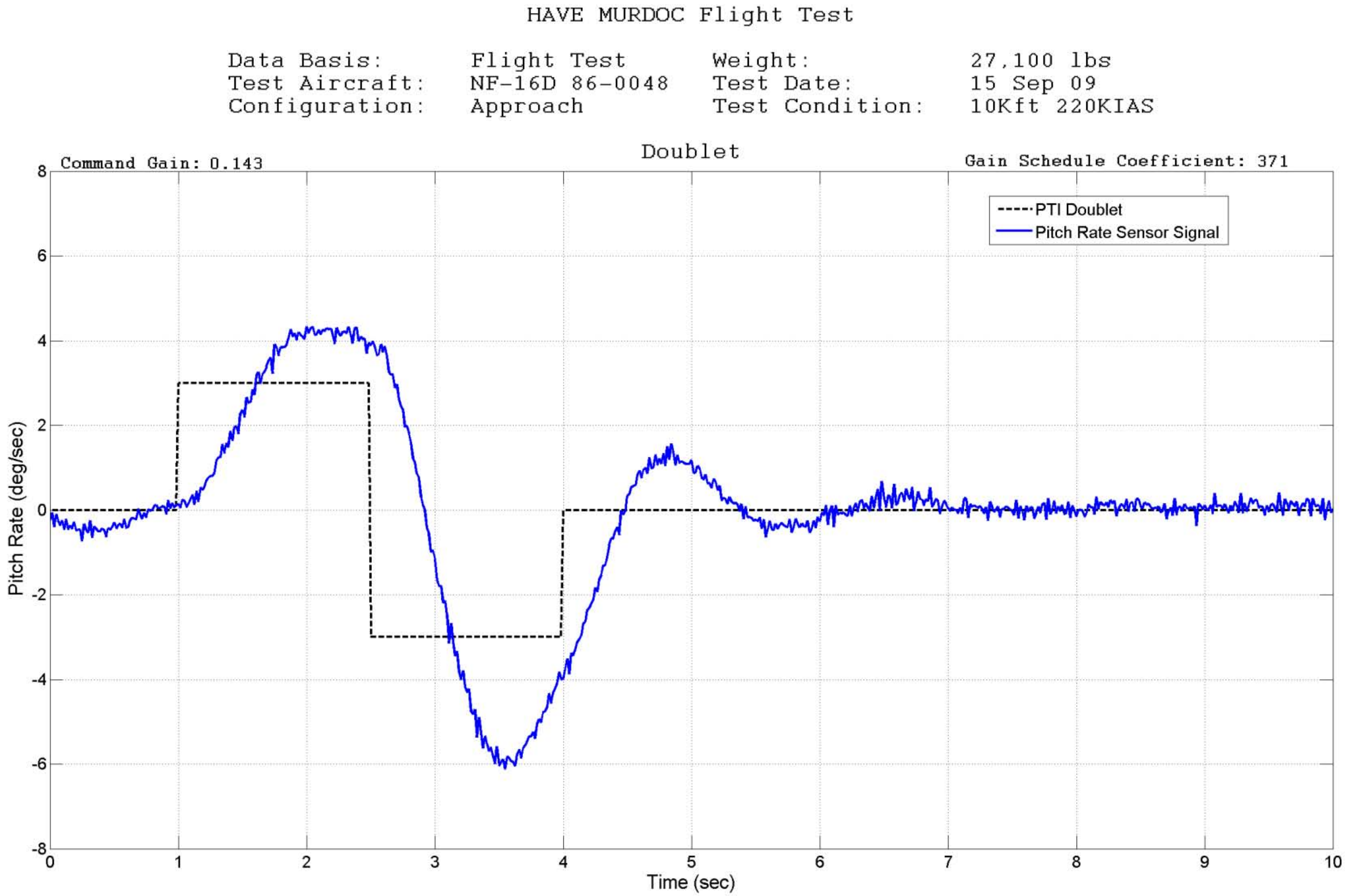



**Figure C-25: Doublet (10K, 220KIAS)**

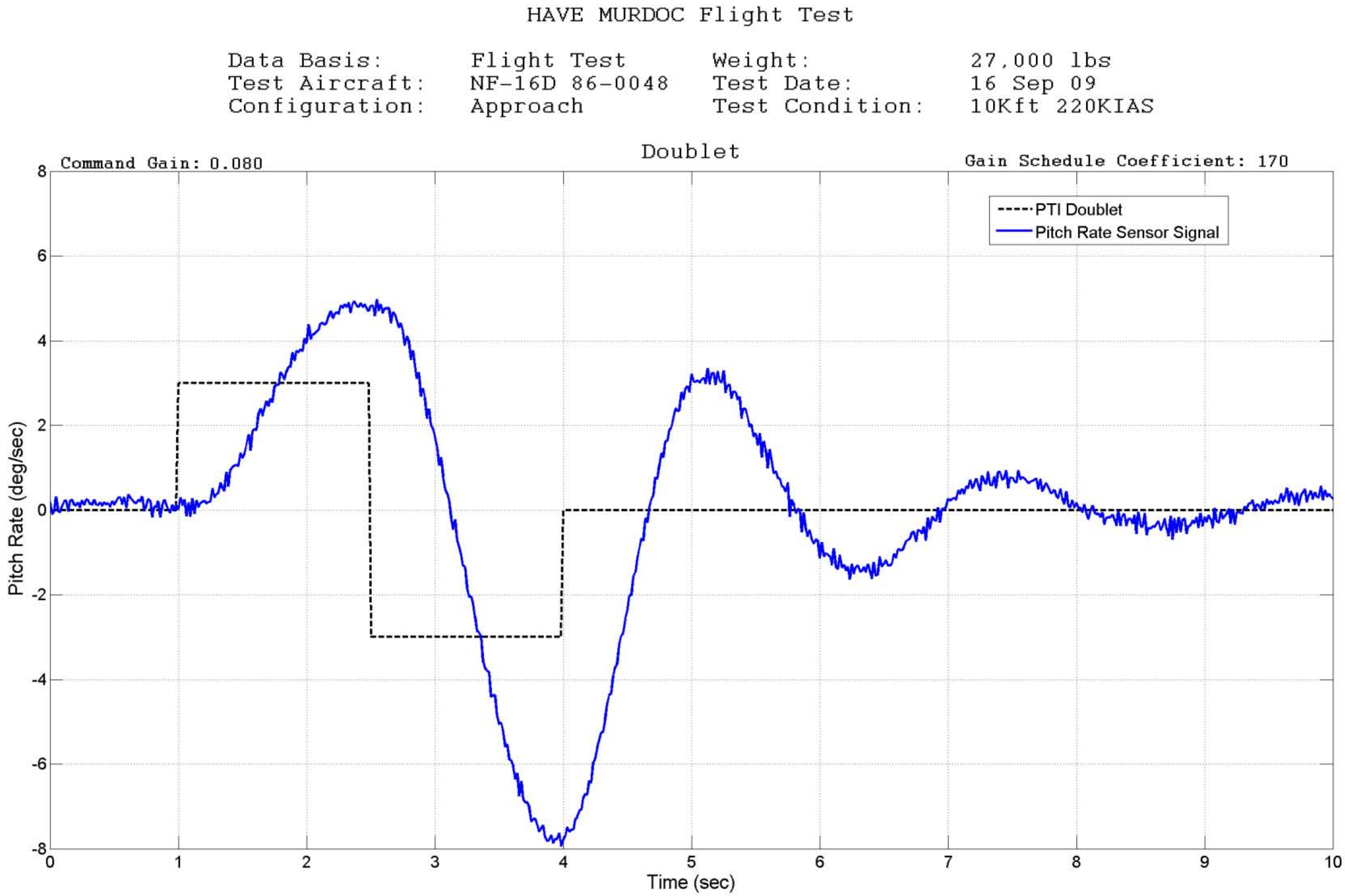



**Figure C-26: Doublet (10K, 220KIAS)**

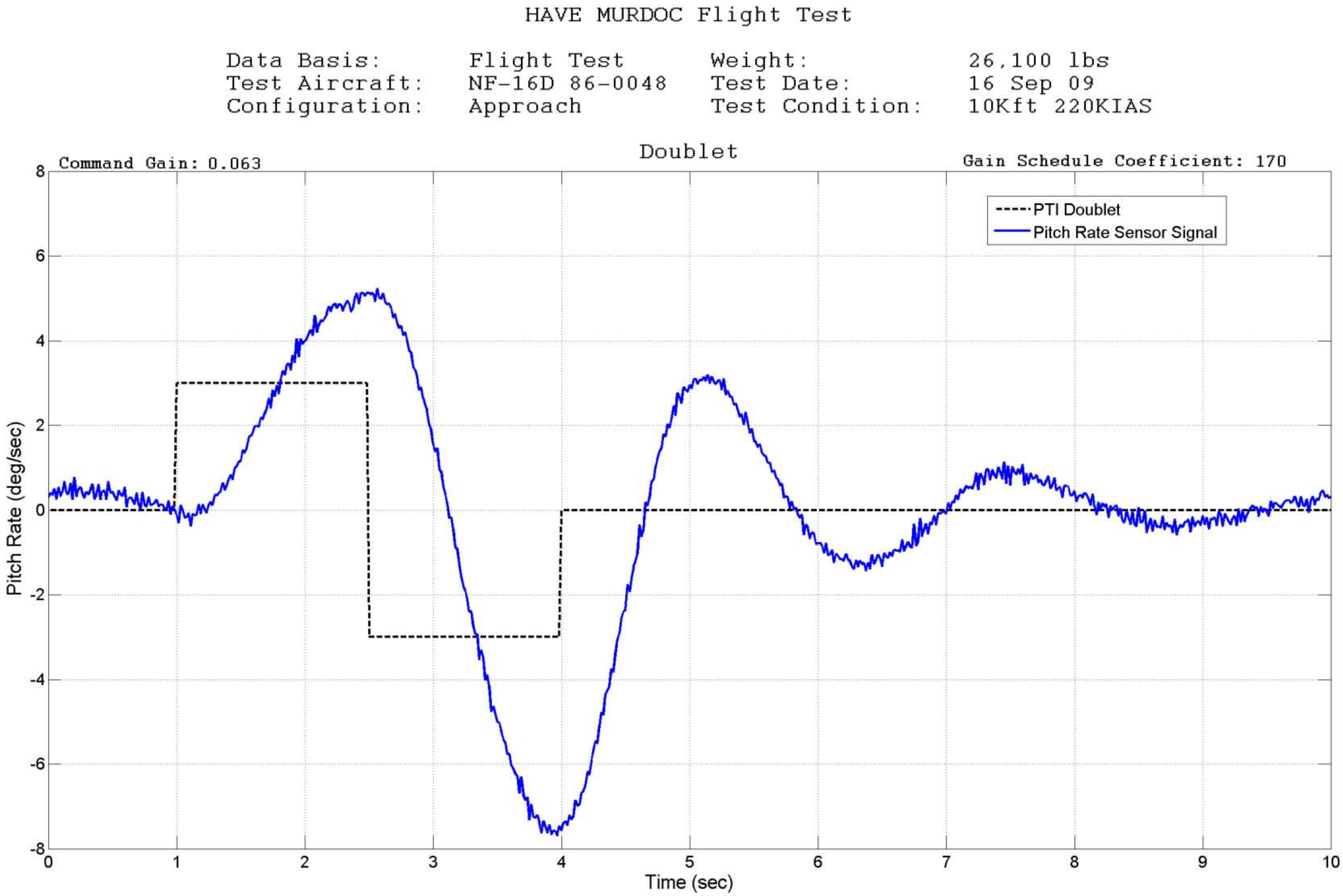



**Figure C-27: Doublet (10K, 220KIAS)**

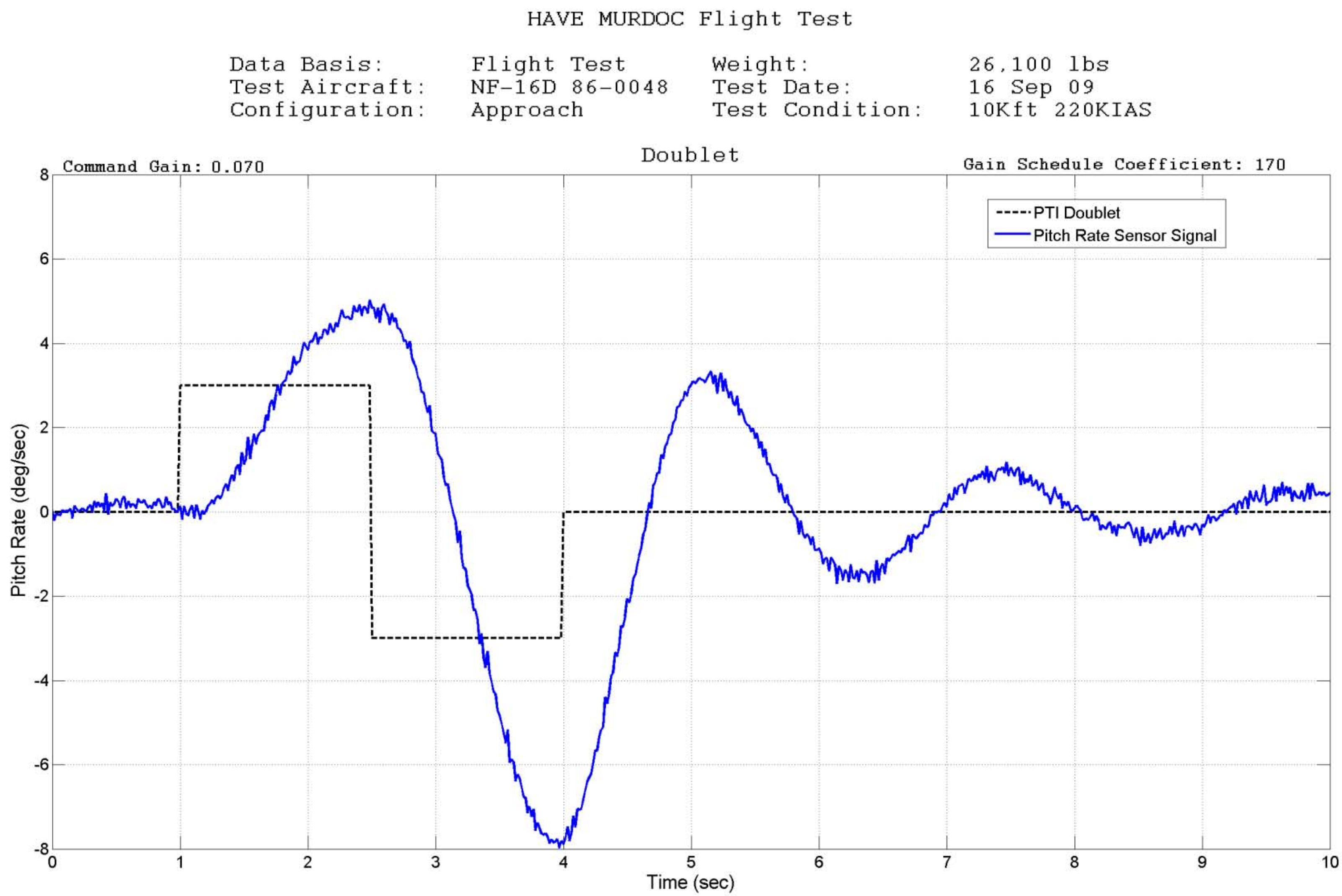



**Figure C-28: Doublet (10K, 220KIAS)**

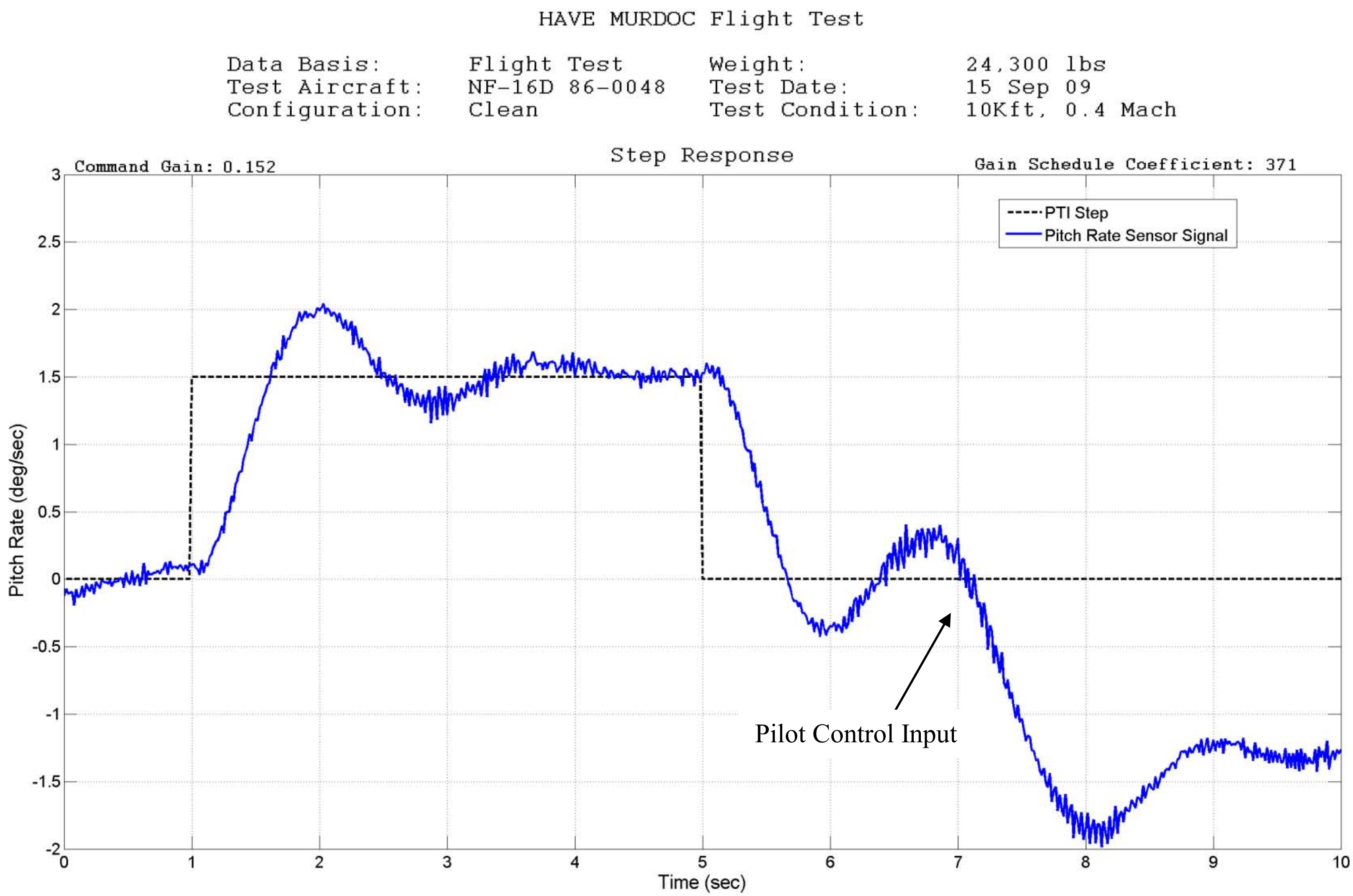



**Figure C-29: Step (10K, 0.4 Mach)**

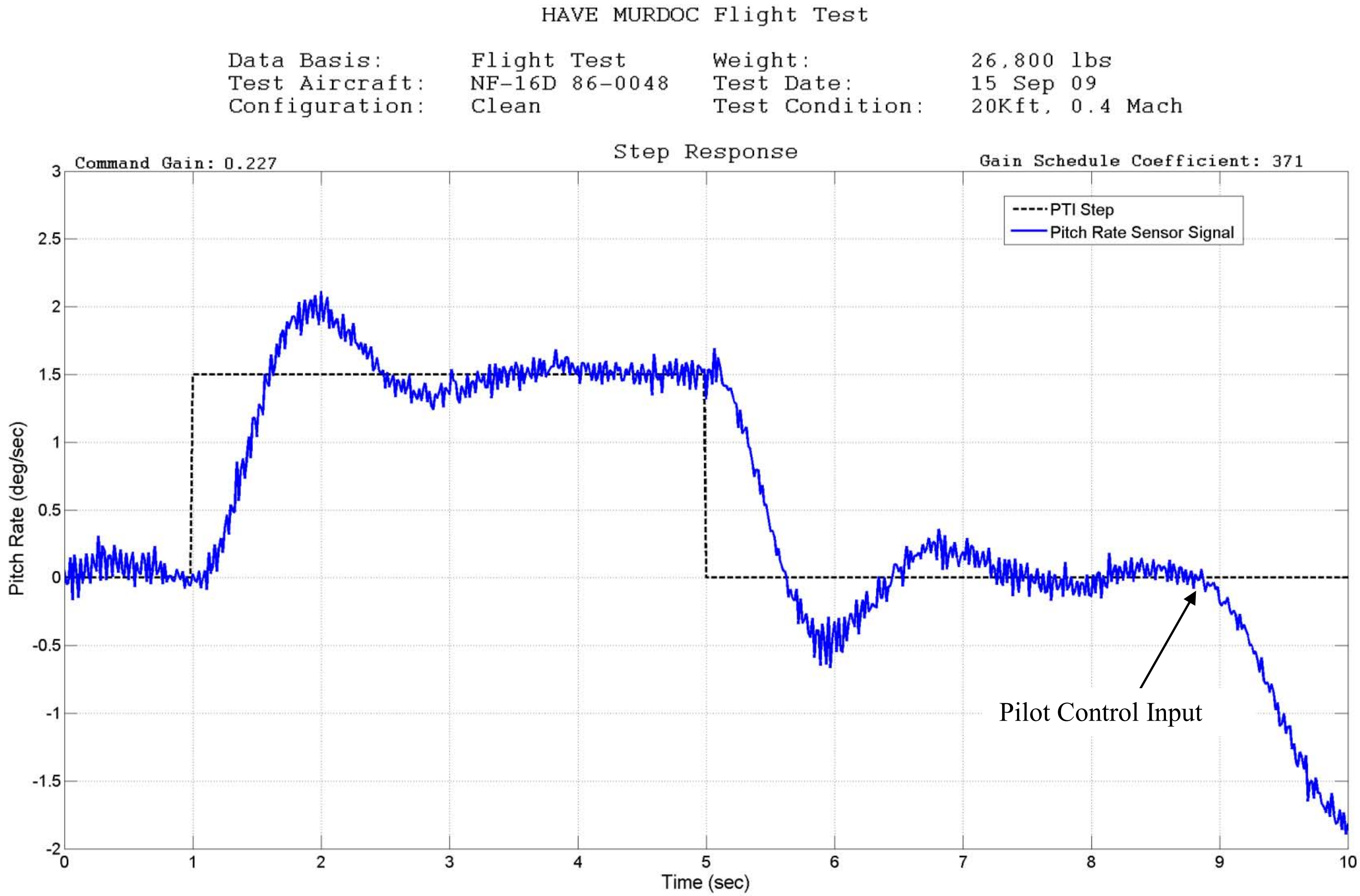



**Figure C-30: Step (20K, 0.4 Mach)**

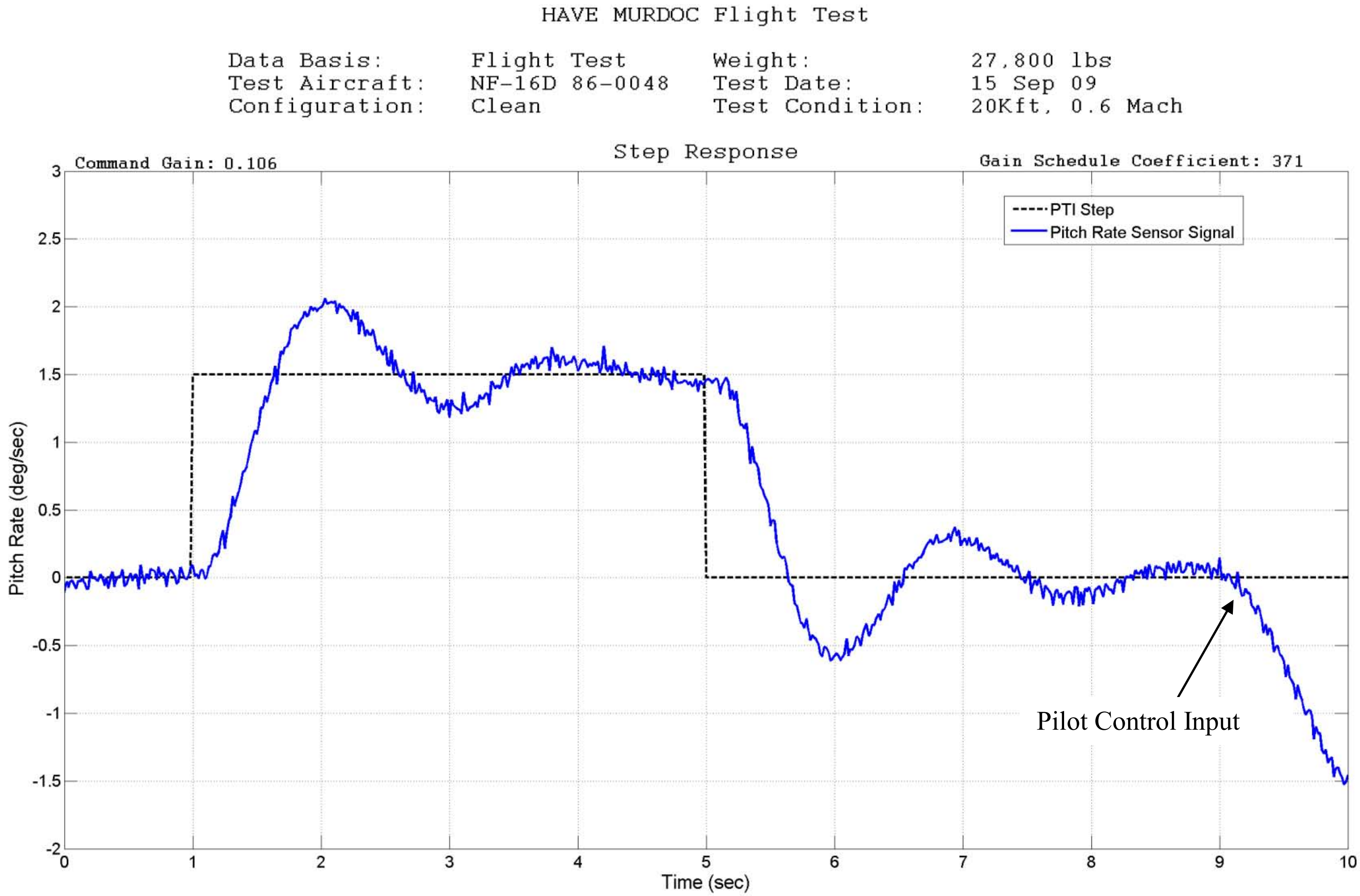



**Figure C-31: Step (20K, 0.6 Mach)**

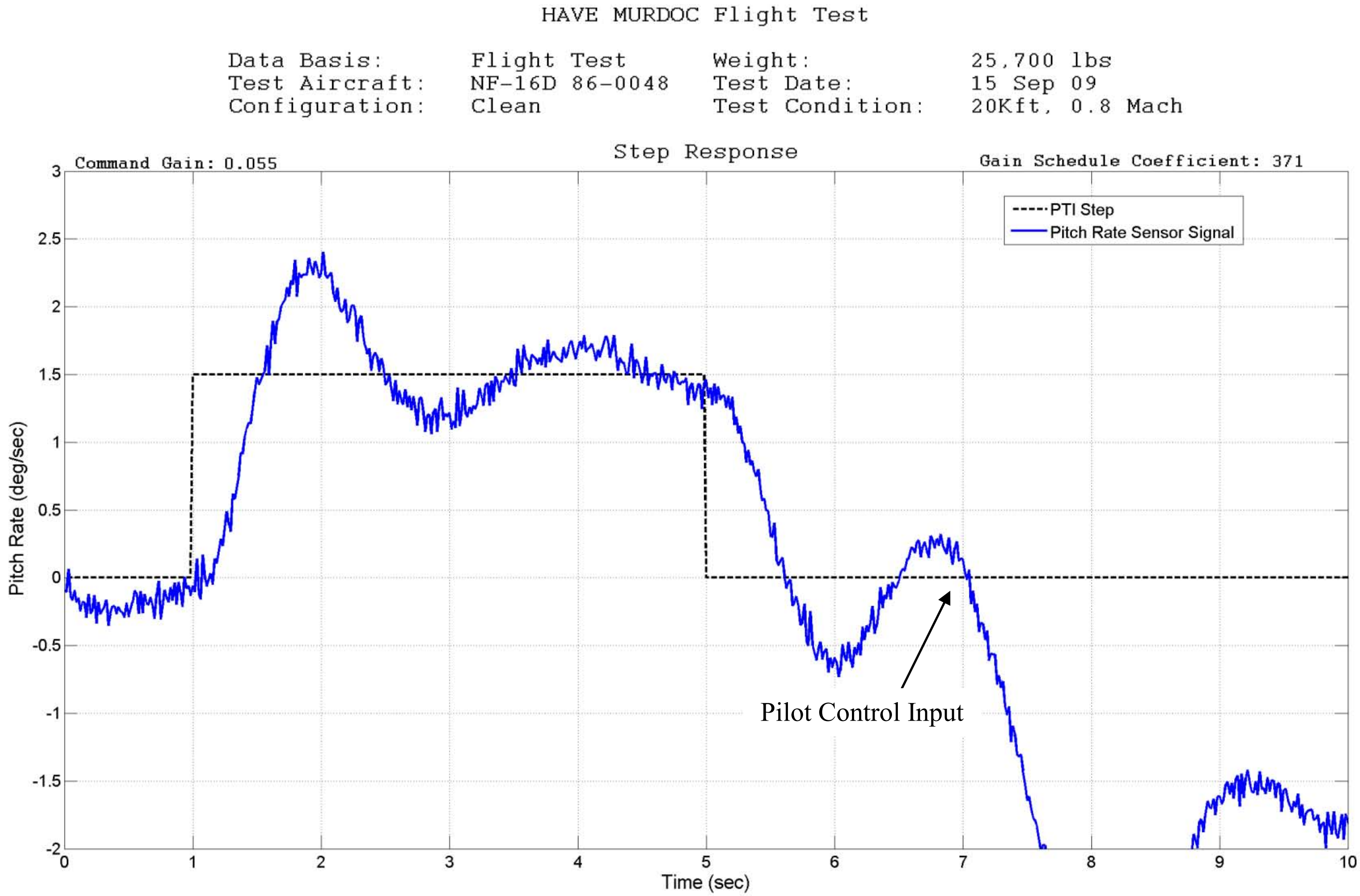



**Figure C-32: Step (20K, 0.8 Mach)**

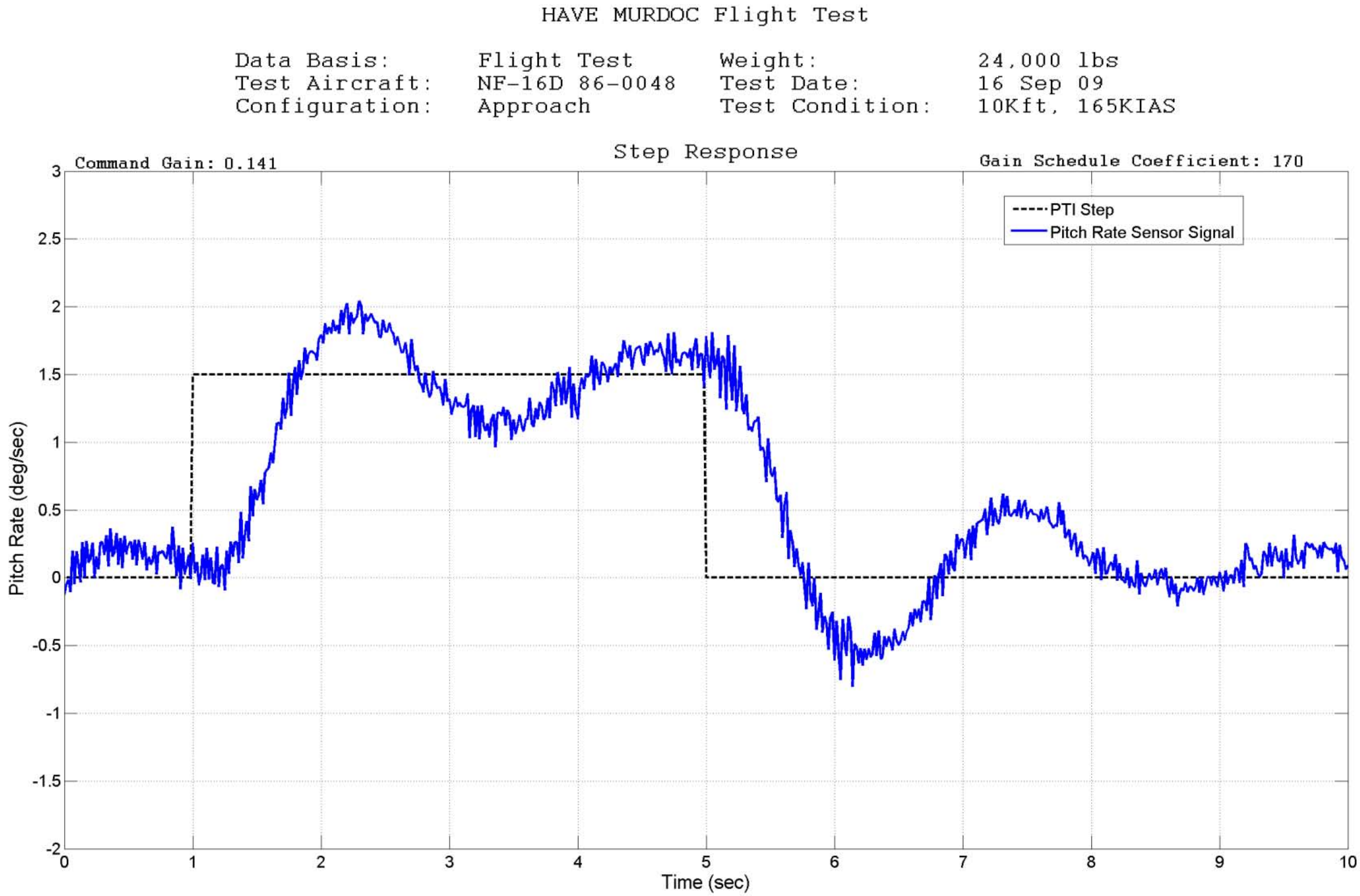



**Figure C-33: Step (10K, 165KIAS)**

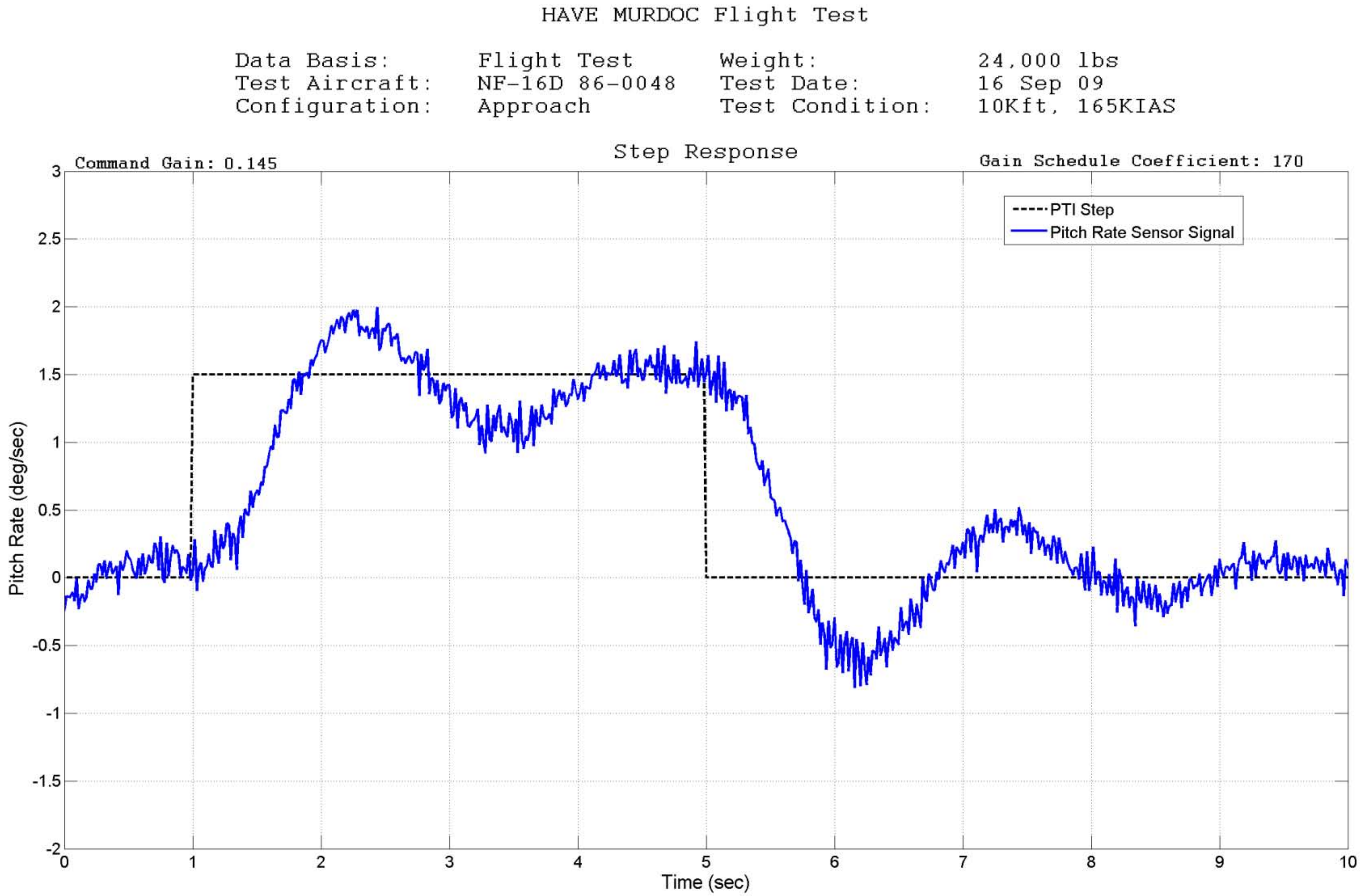



**Figure C-34: Step (10K, 165KIAS)**

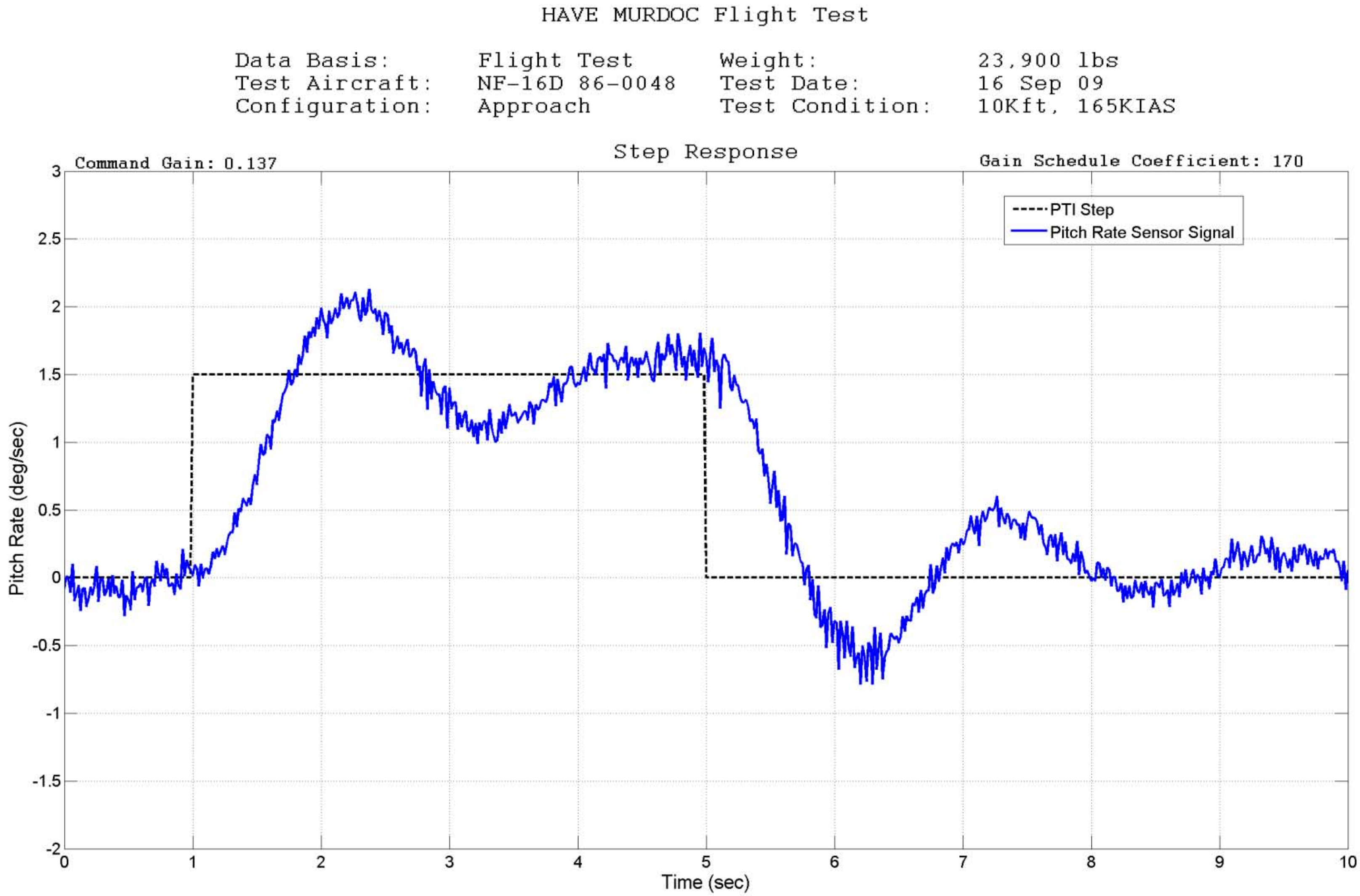



**Figure C-35: Step (10K, 165KIAS)**

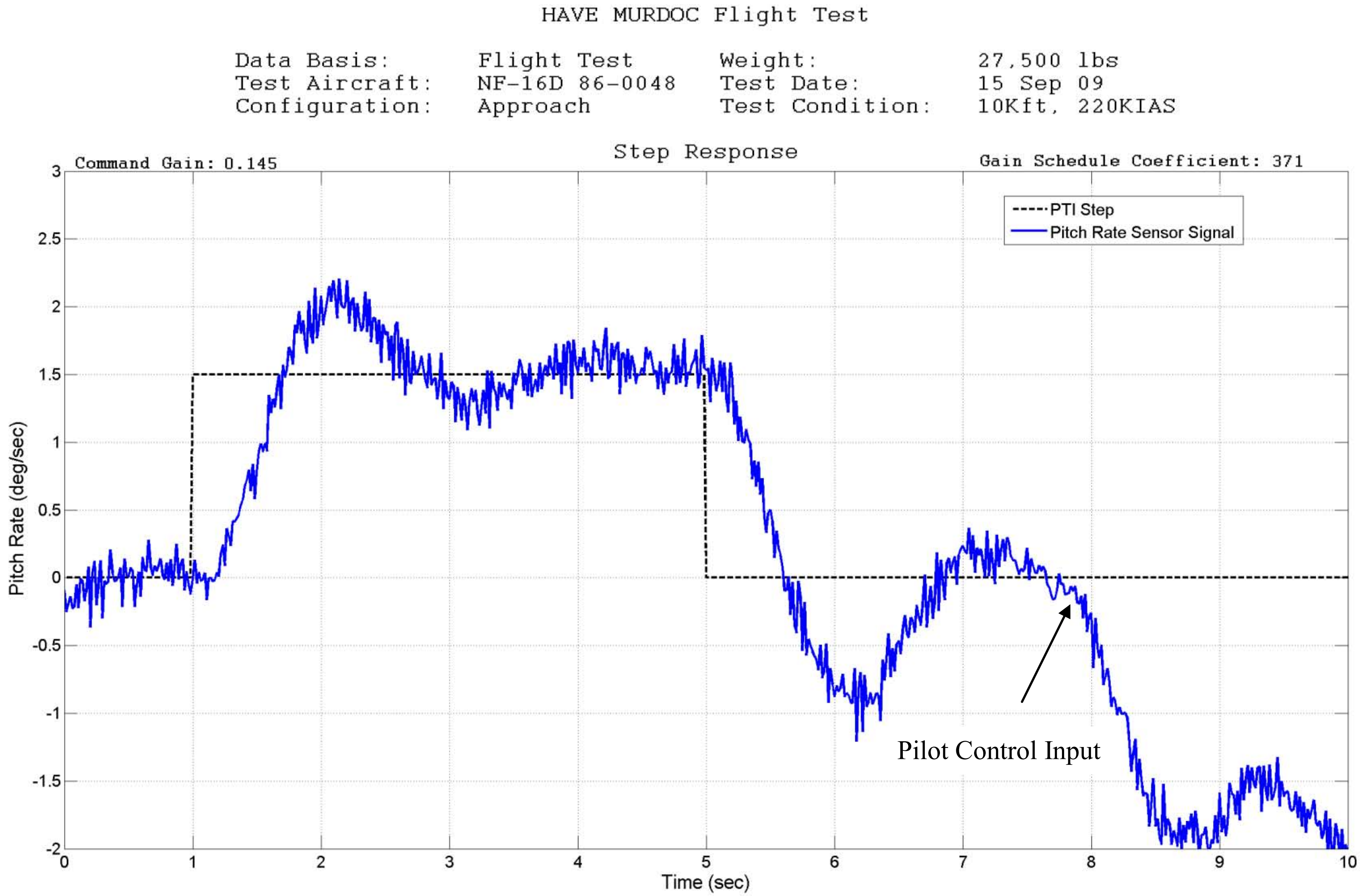



**Figure C-36: Step (10K, 220KIAS)**

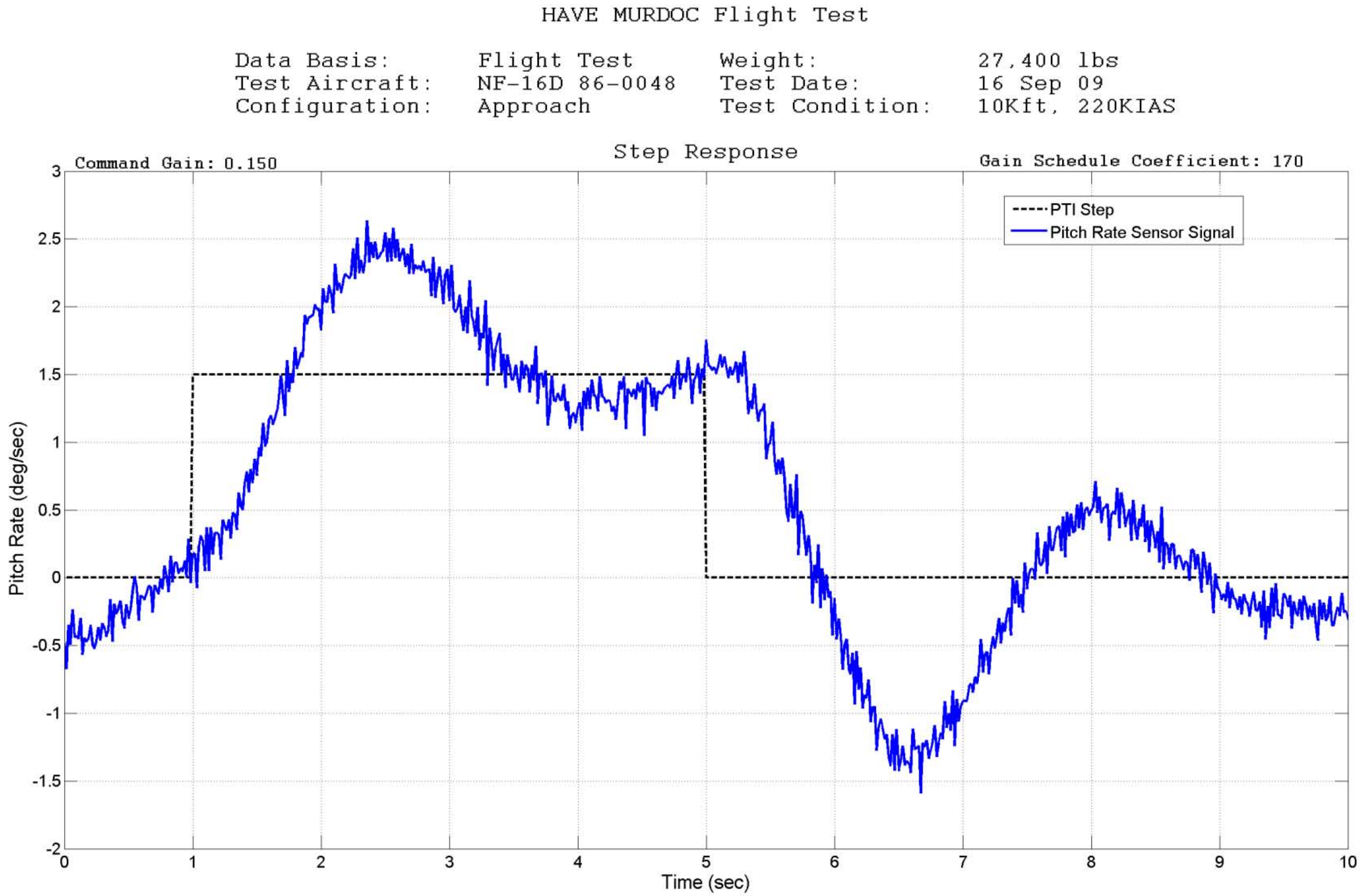



**Figure C-37: Step (10K, 220KIAS)**

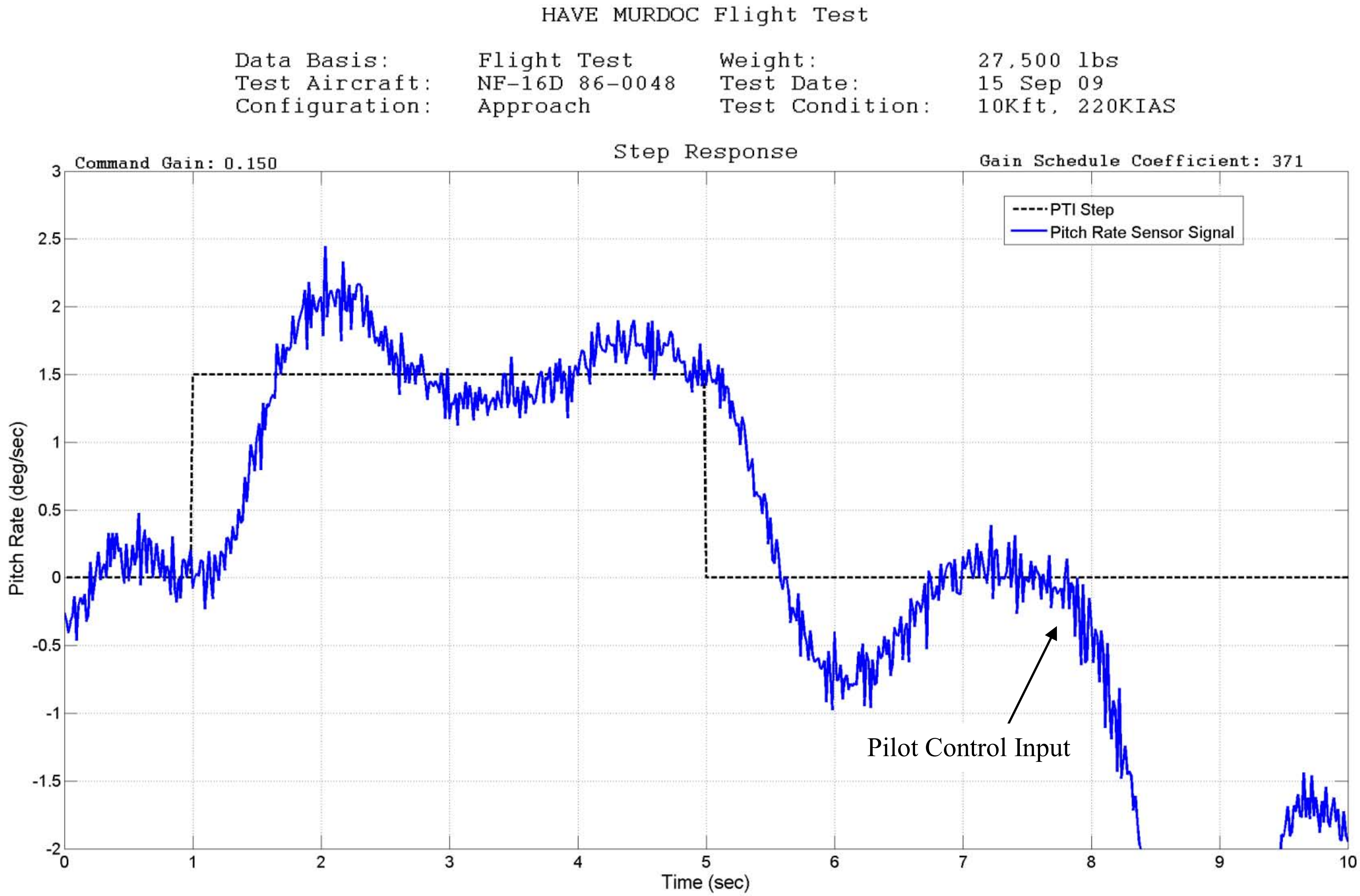



**Figure C-38: Step (10K, 220KIAS)**

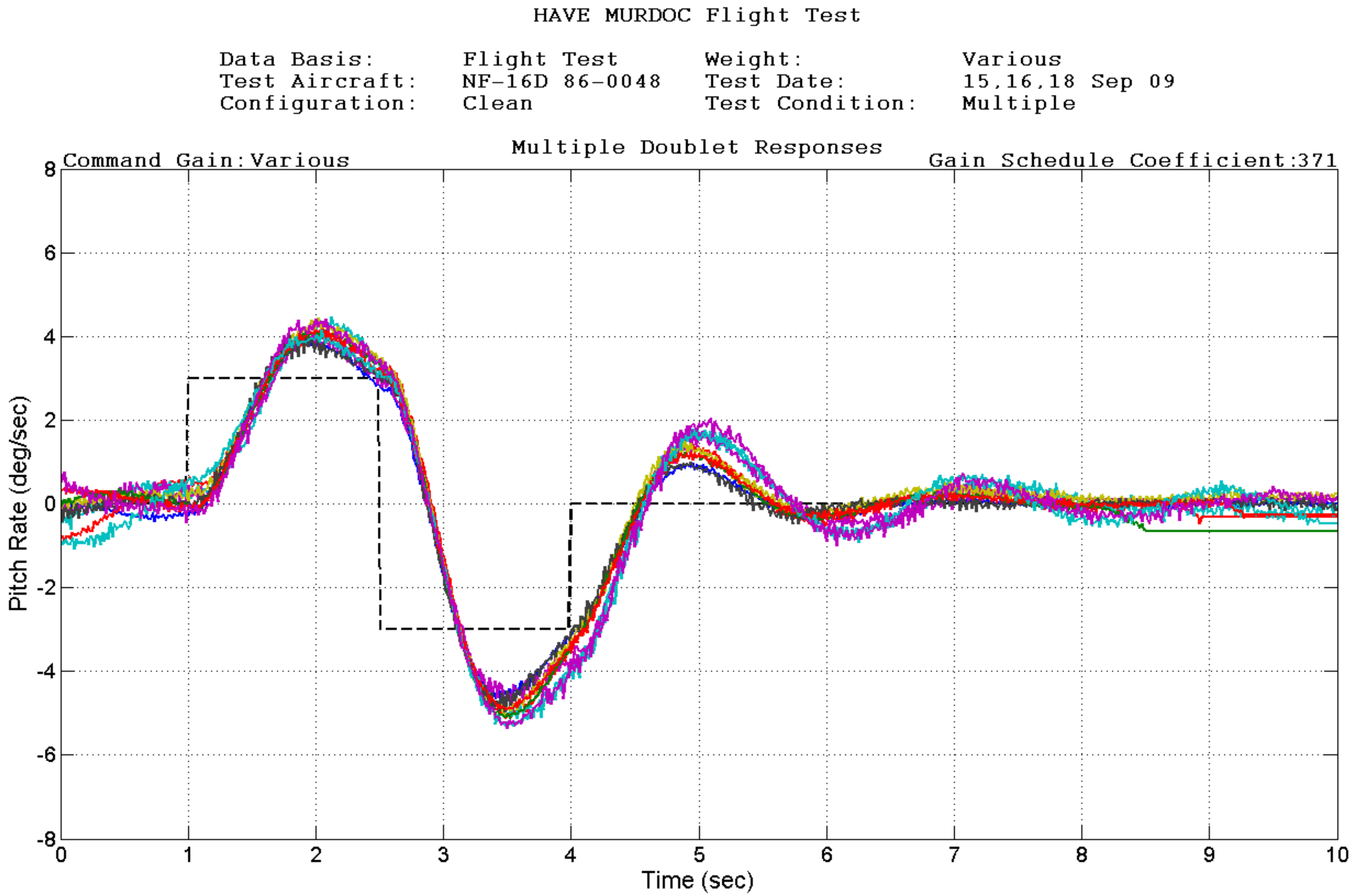



**Figure C-39: Multiple Cruise Configuration Doublets**

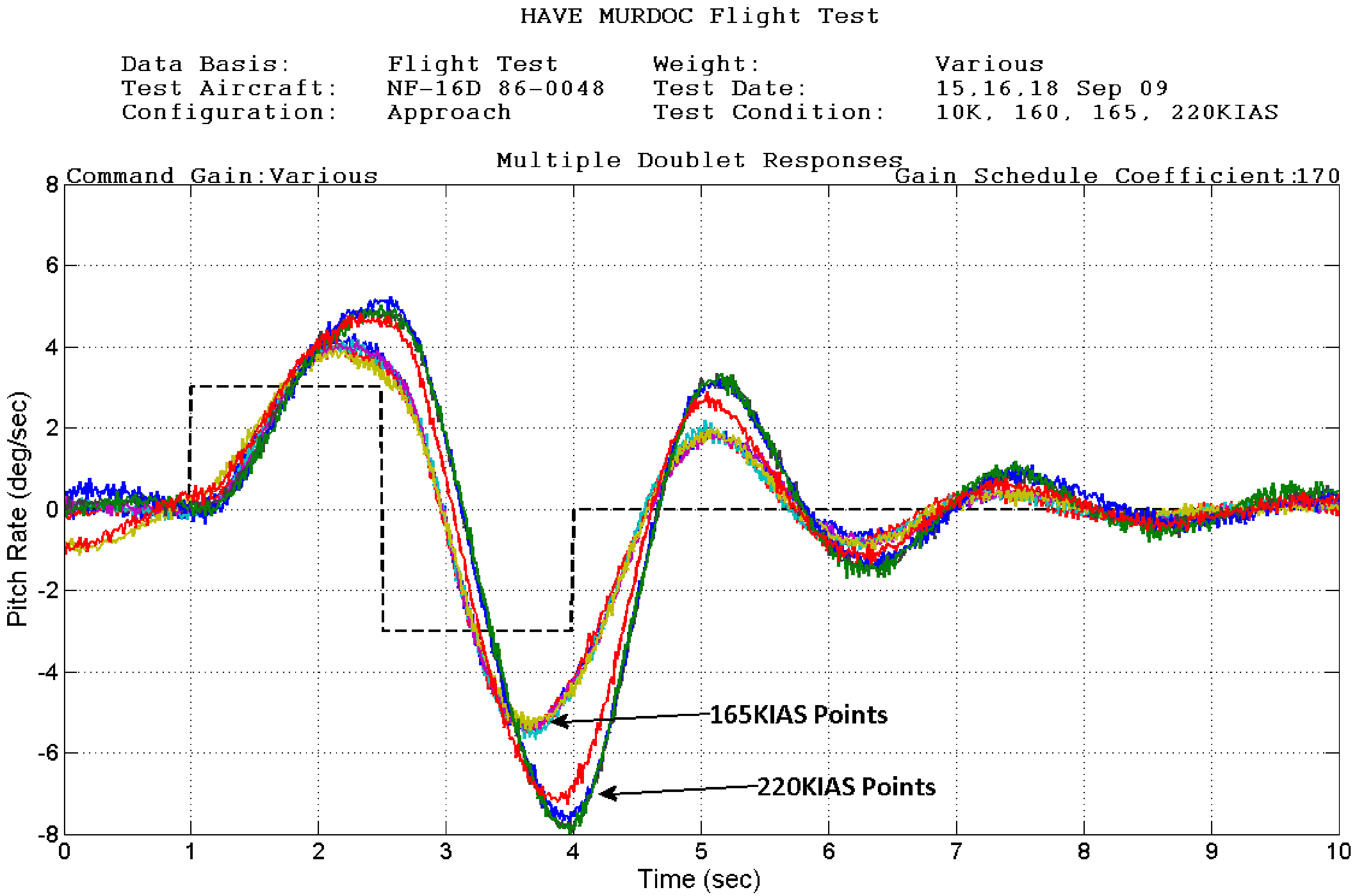



**Figure C-40: Multiple Approach Configuration Doublets**

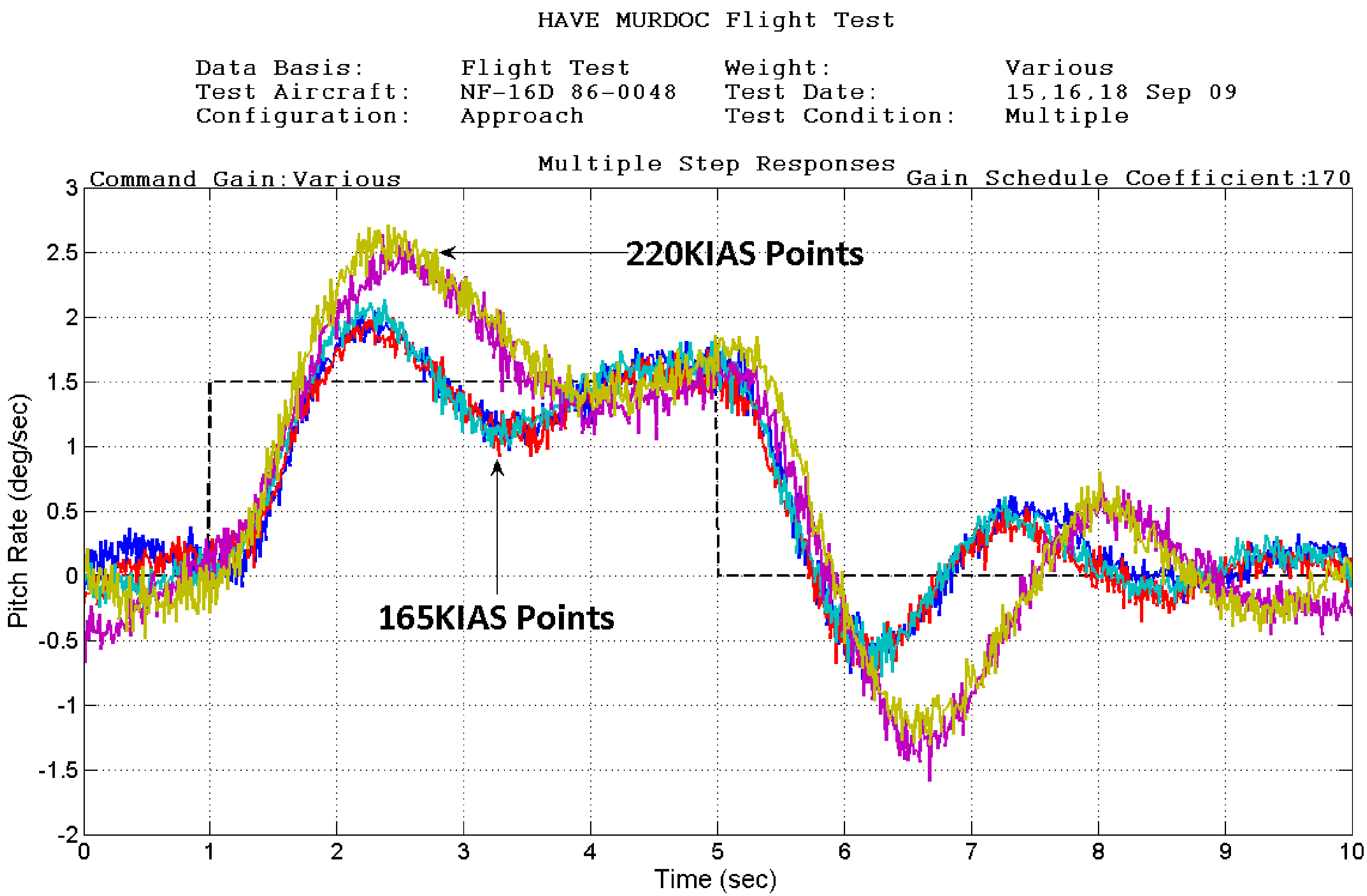
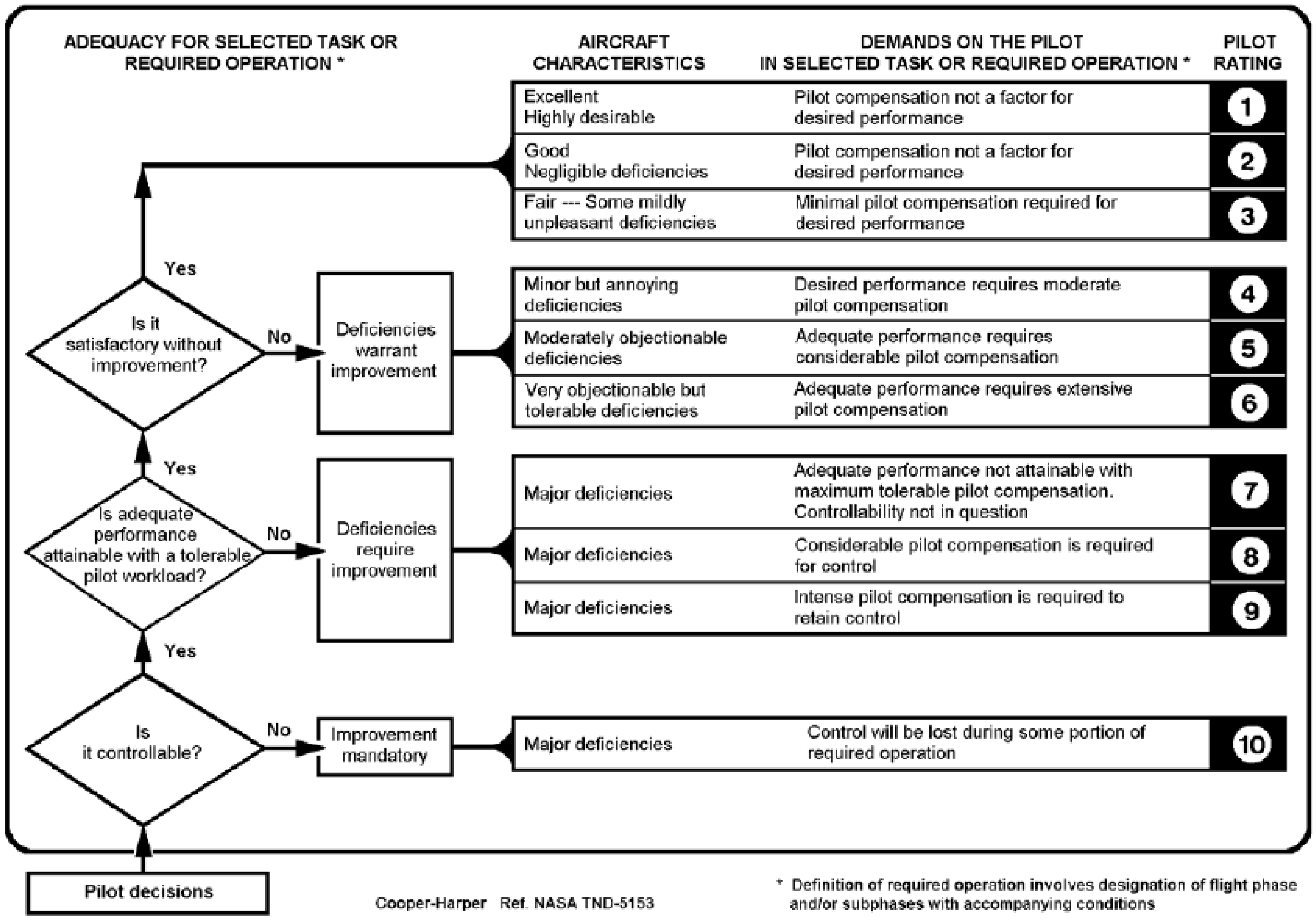



**Figure C-41: Multiple Approach Configuration Steps**

# APPENDIX D – Cooper-Harper Rating Scale



# APPENDIX E – PIO RATING SCALE

**Did I experience PIO ?**

- **No:**
  - **undesirable motion ?**
    - **no** → **1**
    - **yes**
      - **tend to occur ?** → **2**
      - **easily induced ?** → **3**
- **Yes:**
  - **abrupt or tight control ?**
    - **bounded ?** → **4**
    - **divergent ?** → **5**
  - **normal control ?** → **6**

# APPENDIX F – LESSONS LEARNED

*Pitch Rate Sensor Bias*

With the VSS engaged, a constant nose up pitch rate of approximately 0.25 deg/sec was evident. The pitch trim switch was found to be disabled and pilot compensation was required to maintain zero pitch rate with the VSS engaged. The trim switch was supposed to be enabled for flight test, however, switch function was not available due to a DO/VSS integration oversight. Flight data resulted in the discovery of a pitch rate sensor bias that affected the DO flight. Figure F-1 shows the plot of a typical VSS engagement with an intentional zero input command by the pilot following the transfer of control to the VSS. Prior to the VSS engagement, the stick command signal was centered and set to zero. The safety pilot was flying straight and level, however the pitch rate sensor was sensing approximately -0.2 deg/sec pitch rate. At 6.5 seconds the VSS was engaged and the DO sensed the negative pitch rate and compensated for it by commanding a positive pitch rate even though the pilot was not actuating the control stick.

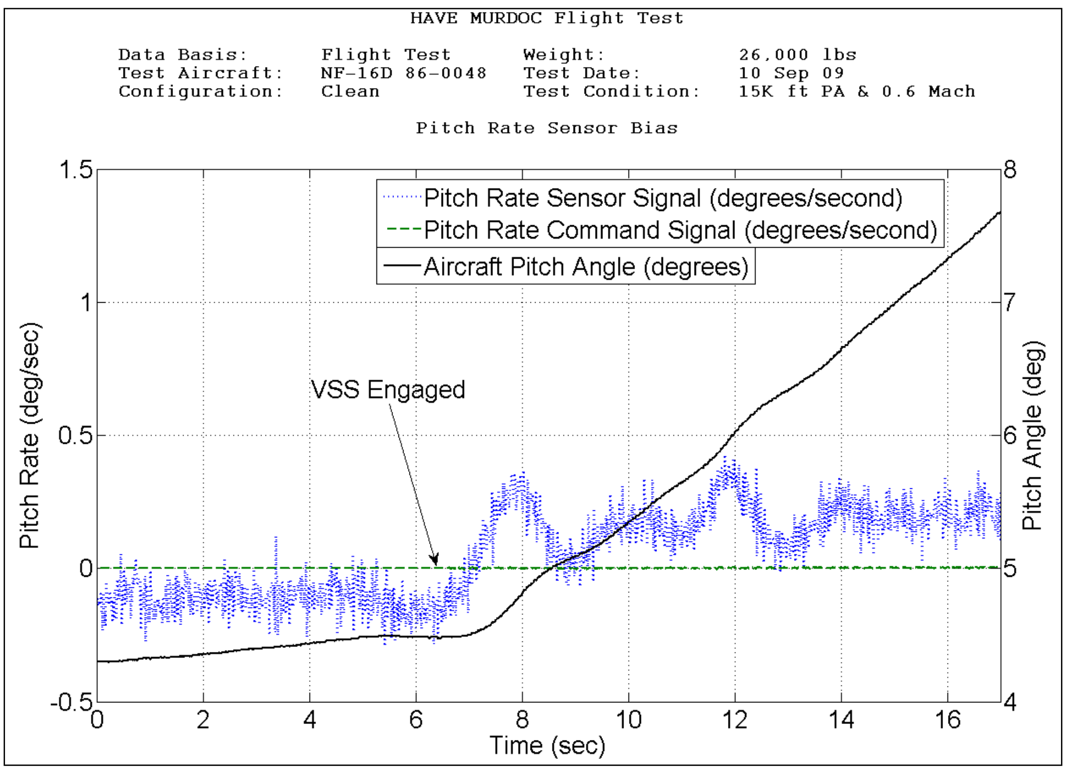



**Figure F-1: Pitch Rate Sensor Bias**

Calspan engineers were able to minimize the effect of the bias for test sorties subsequent to an operational flight program (OFP) change, however the trim switch function was never regained. It was determined that more time to troubleshoot would have led to a Calspan fix to the trim switch issue. All plots containing pitch rate sensor signals were adjusted to reflect this bias. For instance, when plotting a pitch rate response in series with the step or doublet command signal, the pitch rate would display offset from the command by the sensor bias. To calculate accurate damping ratios and frequencies, the pitch rate signal was adjusted by the sensor bias.

*Selection of Test Objectives*

When the test team decided to make „approach and touchdown‟ one of the test objectives, we forced a lengthy handling qualities investigation that had little to do with the disturbance observer and more to do with buildup to ensure a safe approach to landing. The focus of the last two thirds of the test flights was on evaluating the handling qualities of the DO as designed. The plan did not allow for improving the handling qualities by changing the „desired dynamics‟ of the controller (a unique capability of the DO that is easily accomplished with the VISTA). The desired damping ratio and frequency could have been changed as easily as initiating a PTI with the VSS. Rather than conducting a handling qualities evaluation on a controller variable that had poor damping, much more could have been gained by adjusting the desired dynamics and conducting PTIs to evaluate the differences. The test team failed to properly generate appropriate test objectives for this project and were enticed by the prospect that taking a new flight controller to landing would bring credit to the project. As it was, the controller was branded by poor handling that required the pilots to keep their gain low while flying the approach.

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